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Amplification of strong ground motions at Heathcote Valley during the 2010-2011 Canterbury earthquakes: The role of 2D non-linear site response

--Manuscript Draft--

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Abstract:	This article presents a quantitative case study on the site amplification effect observed at Heathcote Valley, New Zealand, during the 2010-2011 Canterbury earthquake sequence for 10 events that produced notable ground acceleration amplitudes up to 1.4g and 2.2g in the horizontal and vertical directions, respectively. We performed finite element analyses of the dynamic response of the valley, accounting for the realistic basin geometry and the soil non-linear response. The site-specific simulations performed significantly better than both empirical ground motion models and physics based regional-scale ground motion simulations (which empirically accounts for the site effects), reducing the spectral acceleration prediction bias by a factor of two in short vibration periods. However, our validation exercise demonstrated that it was necessary to quantify the level of uncertainty in the estimated bedrock motion using multiple recorded events, to understand how much the simplistic model can over- or under-estimate the ground motion intensities. Inferences from the analyses suggest that the Rayleigh waves generated near the basin edge contributed significantly to the observed high frequency (f>3Hz) amplification, in addition to the amplification caused by the strong soil-rock impedance contrast at the site fundamental frequency. Models with and without considering soil non-linear response illustrate, as expected, that the linear elastic assumption severely overestimates ground motions in high frequencies for strong earthquakes, especially when the contribution of basin edge-generated Rayleigh waves becomes significant. Our analyses also demonstrate that the effect of pressure-dependent soil velocities on the high frequency ground motions is as significant as the amplification caused by the basin edge-generated Rayleigh waves.
Author Comments:	Please note that there is a bug in the 'biblatex' package installed on the LaTeX build system, which puts a strange comma between the name and the year. For example, it creates "Bradley, (2015)" instead of the intended "Bradley (2015)"
Suggested Reviewers:	
Opposed Reviewers:	
Response to Reviewers:	I will upload the response to reviewer as a pdf file.

Response to reviewers

We thank the reviewers for their constructive and thorough review comments. We believe that the quality of the manuscript improved significantly by addressing those comments. We have written our detailed responses to the reviewers' comments in the following paragraphs. For the ease of reading, all our responses are written in red color.

Reviewer #1

This manuscript presents a detailed analysis on the response of the Heathcote Valley during the 2010-2011 Canterbury earthquakes through comparisons of observations and synthetics. The observations correspond to strong motion signals from 10 different earthquakes with moment magnitudes between 4.7 and 7.1, with particular emphasis on the ground response at two sites, namely stations HVSC in the valley and LPCC at a reference rock salient location. The synthetics correspond mainly to simulations done with a two-dimensional model, but also include discussions about complementary efforts done using one- and three-dimensional modeling. The authors find interesting results and present relevant conclusions regarding site effects and the role of the shallow soft material deposits.

The manuscript is fairly well written and the analysis is thoroughly carried out. The submission, nonetheless, needs some improvements, minor overall, except for a request regarding additional detailed information about the 2D numerical model, and the material models, which are currently not fully described. It is the recommendation of this reviewer that the submission be considered for publication once the authors have addressed the following comments.

Main Comments:

1. P1, L2. Consider "This article presents a quantitative case study" to avoid double "study".

Reply: Accepted.

2. P1, L12. "suggest" instead of "suggests".

Reply: Accepted.

3. P3, L30-31. Avoid nested parenthesis.

Reply: Accepted. The sentence is now broken into two separate sentences: "The high intensity of this ground motion record may be attributed in part to the proximity of the earthquake source, as the source-to-site distance, Rrup, was only 3.9km, based on the finite fault model of (Beavan, 2012).

Nevertheless, the peak accelerations may still be considered unusually high given the relatively moderate earthquake magnitude of Mw6.2."

4. P3, L35. Should be "Bradley (2015)" and not "Bradley, (2015)". (This extra comma appears in all text citations. Parenthesis citations are correctly formatted, but not the text citations. Please correct throughout the whole manuscript.)

Reply: This was caused by a bug in one of the latex packages used in the online submission system. It will be fixed in the final proofing stage.

5. P4, L68. Consider using a shorter title. Perhaps "Evidence of site effects at Heathcote Valley".

Reply: Changed to "Observational evidence of site effects at Heathcote Valley". Although we agree that the section titles shouldn't be unnecessarily long, we also prefer the section titles to be specific enough.

6. P4, L69. Same suggestion, perhaps "Comparison of recorded ground motions".

Reply: Again, we believe that short titles are desirable as long as it conveys all the necessary information to help readers follow the logic flow of the article. We feel that the suggested section title is a bit too vague (i.e. "with what" is missing) and therefore decided to keep the original section title.

7. P5, L75. "amplitudes" instead of "amplitude".

Reply: Accepted.

8. P5, L81-82. Again, a suggested shorter title: "Amplification and mode conversion".

Reply: Shortened to "Amplification and mode-conversion caused by shallow inclined valley geometry".

9. P5, L86-87. Perhaps this being the first instance in which GeoNet is mentioned, you could add at the end something to make it "(GeoNet public ID 3372561, see the Data and Resources section)".

Reply: Accepted.

10. P5, L85. I would suggest avoid starting a new sentence again with "Figure 4 shows...". Consider "In particular, this figure shows...".

Reply: Accepted.

11. P6, L100-103. The sentence "Bradley... and Brune, 1999)" does not read well. Please consider rephrasing.

Reply: Accepted, and rephrased into "Taking advantage of the abundance of recorded earthquakes during the 2010-2011 Canterbury earthquake sequence, Bradley (2015) demonstrated the systematic site effects of 20 strong motion stations, including HVSC, by relaxing the conventional ergodic assumption (Anderson, 1999)."

12. P6, L104-105. Please add punctuation to the end of the equation (a comma), so it reads with the flow of the sentence. (Apply this to all subsequent equations.)

Reply: Accepted.

13. P6, L110. Shouldn't it be "HVSC" instead of "Heathcote Valley"? And by "all stations" you mean all the stations in Figure 2?

Reply: Accepted. All stations considered in the empirical study by Bradley (2015).

14. P6, L110-111. "events" or "earthquakes" but not both as in "earthquake events".

Reply: Accepted. "for all events considered."

15. P6, L114. Change to "Considering that the local geology of Heathcote Valley is characterized...".

Reply: Accepted.

16. P6, L115. Perhaps it would be better to say "Port Hills volcanic bedrock" instead of "Port Hills volcanics"?

Reply: Accepted.

17. P6, L116. Delete "over volcanic rock", seems unnecessary.

Reply: Accepted.

18. P6, L118. Delete the comma, splits the sentence unnecessarily.

Reply: Accepted.

19. P6, L118. It seems to me this section needs closing. It reads as unfinished.

Reply: Accepted. Moved the last paragraph to the top to address this.

20. P7, L119. Consider shortening the title to simply "Comparison with broadband ground motion simulations".

Reply: Accepted.

21. P7, L122. "using the" instead of "using a".

Reply: Accepted.

22. P7, L122, L123. Try avoiding the proximity of "using" and "Using".

Reply: Accepted. Rephrased to "Taking advantage of a recently developed ..."

23. P7, L133. I suspect is "those" instead of "the use".

Reply: Accepted.

24. P7-P9. Section "Model description". Here is the first of only a few substantial criticisms to the manuscript. This section lacks important details about the model. Relevant unanswered questions include: What is the minimum size of elements? What is the number of points per wavelength used in the discretization? What is the target maximum frequency? What is the total number of elements? What type of elements were used in the mesh? Only quadrilaterals or also triangular, linear or quadratic? Was the mesh built using OpenSees or some other external mesher? How was the quality of the elements guaranteed, especially at the edges where others have shown wedges with strong material contrasts can lead to numerical instabilities? Could figure 8 include an inset showing the detail at the basin's edge(s)? These latter two questions can be critical given that at this point the contrast of shear wave velocities is about 200 to 800 m/s, which is a factor of 4. What is the \Delta t and number of time steps? It

would be relevant to know the difference in time discretization and running time between a linear elastic and the nonlinear simulations, and the theoretical critical time-step size and how far is the model from approaching the limits of numerical instability both in space and time in order to have a relative sense of the convergence of the model, or simply have a sentence explaining how the authors consider the issue of convergence (if necessary). Alternatively, if there could be any way of showing that there was some level of verification done, this section would be stronger. It would not hurt to mention something about the computational resources used in terms of time and number of processors (if done using parallel computers, as one may infer from the Acknowledgements section).

Reply: We fully agree with the reviewer's comments in that describing the specific details of the model would significantly improve the manuscript and help readers. We updated the main text according to the reviewer's suggestions.

To answer the reviewer's questions:

- The target element size is 2 metres for soil and 5 metres for rock.

- In the soil domain we target 4 elements per wavelength, that is 8 integration points per wavelength as we utilize 4 node quadrilateral elements. The minimum wavelength is then 8 metres, and therefore the maximum frequency is at least 200/8=25Hz. Also, the Vs/dx ratio is much larger for rock elements, so the element size of rock shouldn't be a controlling factor.

- 24866 elements in total. 14306 elements in the main domain. All four-node quadrilateral elements.

- We used the GiD (http://www.gidhome.com). This information is now added in the Data and Resources section: "The finite element mesh is generated using the GiD pre/post processor (http://www.gidhome.com)."

- For time integration we used the implicit Newmark-beta method, which is unconditionally stable. dT is 0.005s, and the number of time steps are 16384. Since we use the unconditionally stable scheme, the time-step size is irrelevent.

- It was not really a large model, so we don't feel that specifying the time and number of cores is relevant. However, to answer the reviewer's question, we used 8 MPI processes for each run and with 8 processes each analysis would take 1~2 hours.

- We simply relied on the unstructured mesh generation algorithm of GiD. However we did check the mesh quality. See Figure 1 that shows the mesh quality as a cumulative distribution of the element min angle. Figure 2 shows the close-up view of the mesh near one of the basin edges.

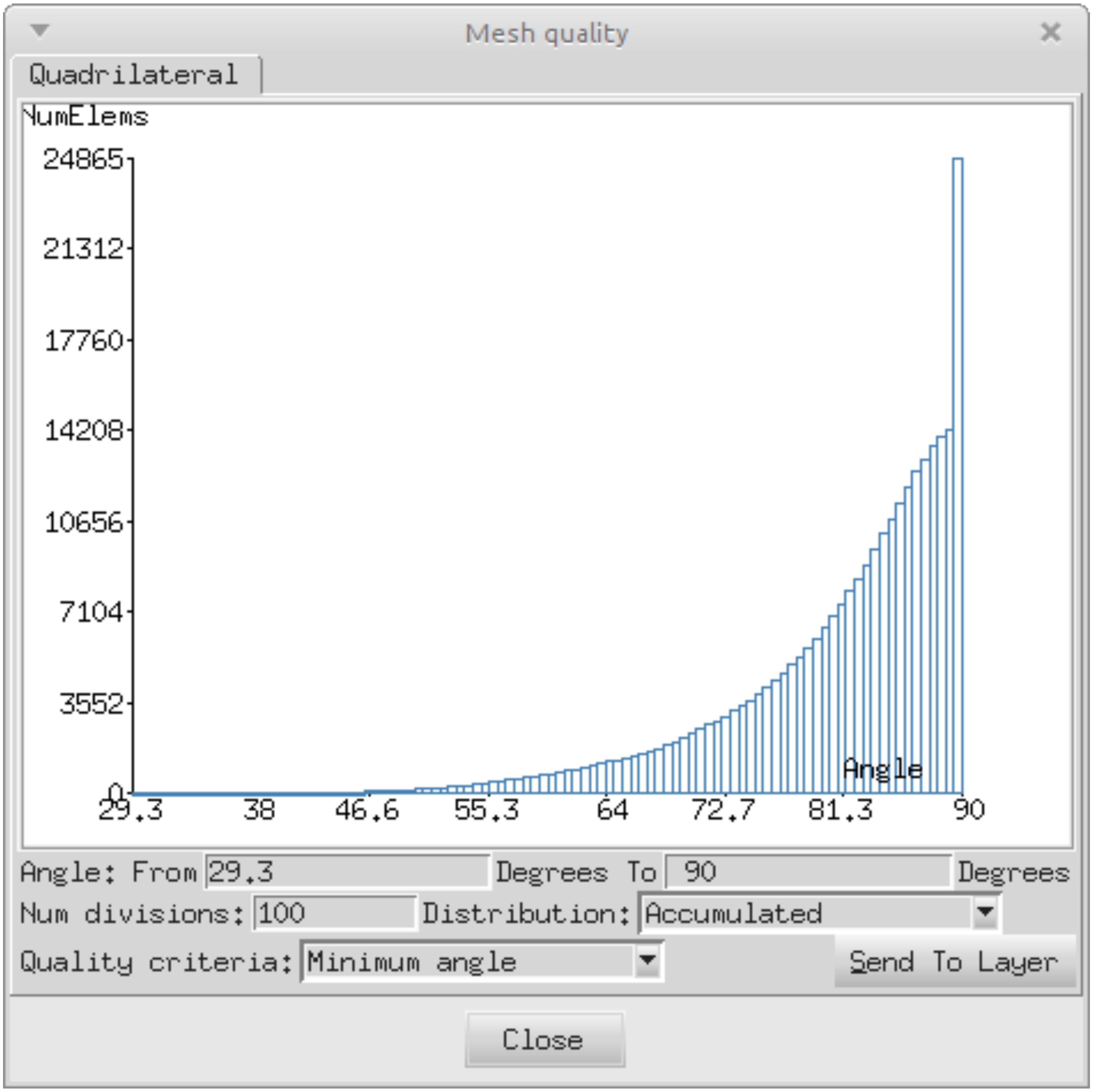

Figure 1 Mesh quality represented by the cumulative distribution of minimum angles.

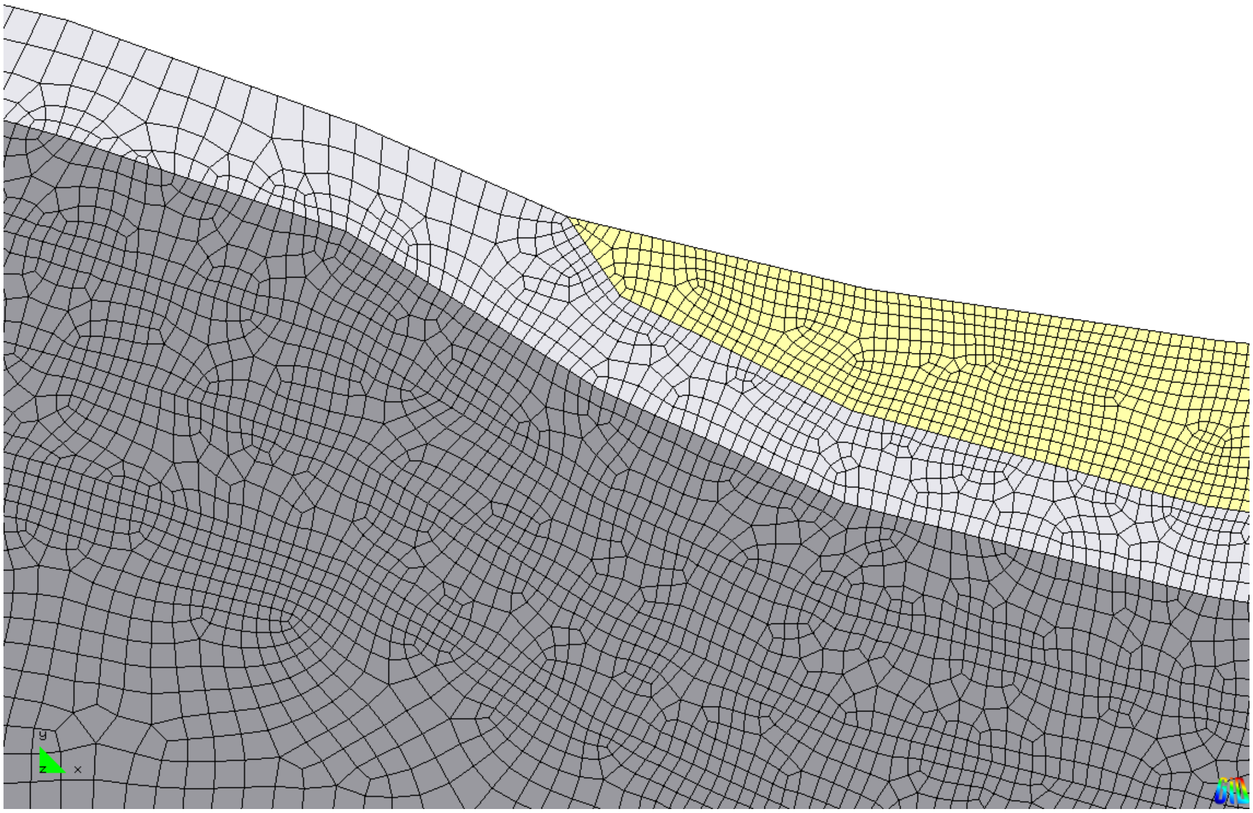

Figure 2 Mesh close-up view near a basin edge.

25. P7-P9. Section "Model description". Still on the same section, but now regarding the model at the element level. Did the authors consider intrinsic attenuation (i.e., damping)? If yes, please describe how, both for the linear elastic case and--more importantly--for the nonlinear simulation (in which case it would be good to know how was Q or the damping ratio changed based on strain). Otherwise, please discuss about the implications of omitting attenuation. Also, please provide more detail about the nonlinear model used to represent the shallower basin deposits, and the initial conditions used. It is said that the pressure dependent multi-yield plasticity model of Yang et al. (2003) was used. Could the authors provide the list of parameters necessary for this model and comment on how were these parameters determined based on data about the valley's deposits. Table 1 includes friction angle and cohesion, is that all? Later, it is said that there is a power-law used to express shear modulus as a function of stress, could it be included? It would be useful to include a figure with the constitutive model, i.e., with a sample or generic plot of the stress-strain relationship used and its hysteritic (loading and unloading) behavior. Also, please describe how were the initial conditions of the model set. I am referring here to initial stress and initial strain at the element level. Considering the model employed is pressure dependent, I assume there most have been some quasi-static pre-consolidation step in the simulations or an equivalent assumption to set such initial conditions.

On a related note, later in the manuscript (P15, L333) it is said that the loess material in Port Hills is pressure dependent and non-plastic. Do you mean non-plastic as in "nonlinear elastic"? The description at the bottom of P8 seems to indicate the contrary, i.e., linear elastic. I am a little confused here because I am assuming that by the loess at Port Hills you are not referring to the shallower deposits in the basin but to the layer beneath it. It may be I misunderstood, but if that is the case then that could be an indication that more details are necessary here.

Reply: There are two different mechanisms of attenuation in the model: the hysteretic damping caused by plastic yielding, and the visco-elastic attenuation which is modelled with a stiffness proportional global damping matrix, that has no damping at f=0Hz, 1% of critical damping at f=15Hz, linearly varying in frequency.

For simulating the response of dry soils with the PDMY model, the only necessary parameters are the initial modulus (or velocity) that is function of effective stress (or depth), friction angle that defines the strength, and a modulus degradation curve that defines how stress-strain curve varies in between the two points. We used the default option for the degradation curve, which is called the modified hyperbolic model (Kondner, 1963). The model also requires some other parametres that are required for simulating the effect of pore water pressure; however these parametres are irrelevent for this study and therefore some recommended (by the model developers) values are used.

We acknowledge the potential usefullness of the figure that describes the constitutive model. However, the manuscript is already too long with many figures. Instead, we included useful references for interested readers to find more information if required.

The reviewer is correct about the model requiring an initial condition. For that reason, the analysis is done in multiple stage. We first perform a linear-elastic gravity analysis with the bottom boundaries fixed (PDMY model in OpenSees has a “switch” that can disable or enable the plasticity during the analysis). After the linear-elastic gravity analysis is done, we then perform the gravity analysis with soil plasticity enabled, to update the stress field to be compatible with the soil plasticity model. After the plastic gravity analysis is completed, we release the fixities of the bottom boundaries and apply the gravity reactions on the boundary nodes to satisfy the static equilibrium. This step is required to implement the absorbing boundary condition and equivalent force input motion.

About the term “non-plastic”, we apologize for causing this confusion. Apparently we used a soil mechanics jargon without properly explaining it beforehand. In soil mechanics, granular soils such as sands and silts are often called "non-plastic". This terminology has nothing to do with the "plasticity" as in solid mechanics, but it rather means it does not behave like clay. We replaced the term “non-plastic” with “granular”.

26. P8, L148. The use of "two dimensional" here made me realize that the terms 1D, 2D, and 3D were not properly introduced at their first appearance in the manuscript. Please check.

Reply: Accepted. The terms 1D and 2D are now introduced in the Introduction section when they are first used.

27. P8, EQ2 and EQ3. I think there should be clarity about something here. The model being 2D, then density is not in units of mass per volume but instead in units of mass per area. In other words, the depth or third dimension of the model is unitary and only nominal. But density is not

much the issue in these equations but the area, A. Unless I am mistaken in my interpretation, in both these equations the area is truly the tributary length of the two elements sharing the node at the boundary or the node at which the force is applied. I assume the computations were done correctly and that the 2D area of the elements was not the quantity used here. Please also add commas at the end of the equations to make them flow with the text.

Reply: The reviewer is correct in that the the off-plane dimension of the model is unitary and nominal, and therefore the the mass density is in the unit of mass per area and the tributary area is really the tributary lengths of the elements sharing the node. The sentence is changed to "... and A is the tributary length of element sides facing the bottom boundary and sharing each boundary node."

28. P8, following EQ3. Consider adding "where $\dot{u}$ is the bedrock input velocity".

Reply: Accepted.

29. P8, L157-158. Later in the manuscript you use the acronym "PDMY", so it would be good to introduce it here.

Reply: Accepted.

30. P8, EQ4. I am puzzled about this. Is the value of VS zero at the free-surface? What is the minimum VS assigned to any element in the 2D model?

Reply: This is a common phenomenological model in soil mechanics that fits lab test data of non-clay soils well. The velocity at the free-surface approaches zero but is undefined, as the velocity is a material parameter that can only be defined between two points of finite distance. The minimum Vs of the element is the Vs corresponding to the minimum mean pressure all elements; the mesh size at the surface is approximately 2m, therefore the minimum Vs is approximately 200m/s.

31. P9, L169. Consider "GeoNet, New Zealand's earthquake monitoring agency, recorded..."

Reply: Accepted.

32. P9, L182-186. Which component of LPCC was used for the deconvolution? Fault normal, fault-parallel, N75E? And what are the implications of using that particular component as opposed to other? Any thoughts worth including?

Reply: We used the N75E component, because the 2D model is along N75E and the two stations are relatively close to each other. In the text, we now added "The recorded LPCC motions are rotated to the azimuth of 75 degrees, as the two stations are relatively close to each other and the 2D model of Heathcote Valley is along that azimuth."

33. P9, L186. Should the empirical relationship used be included here? For completeness-sake, beyond just providing the reference? Just a suggestion, not a strong requirement.

Reply: We considered including a short description of the empirical relationship, but at the end, we concluded that it is unnecessary and potentially distracting. Also, the paper is already a bit too long.

34. P10, L195-197, and Figure 9. Please consider using one of the weakest events too. Figures 9c and 9d are similar in what they show. I would be interested in adding a weak but close event

such as that of 16/04/2011. Adding an earthquake like this could serve as a good reference case to discuss linear response.

Reply: While doing so may seem attractive, we believe that presenting the time domain comparison for individual events for weak events can be misleading because of the large uncertainty. Potential reasons are that 1) the signal quality is not as good for weak events; and 2) the source location is not as good for weak events. Strong events are not as susceptible because they tend to have strong signals, but then we are still showing that they don't compare perfectly. That's why we are presenting the results of multiple events with mean and confidence interval.

35. P10, L204. I would suggest the word "similarities" instead of "agreement", as more appropriate in this case. I would also suggest to change the second part of the sentence regarding the judgment as "overall satisfactory". Perhaps the authors would consider something of the sort of "...the similarities between the simulated and recorded ground motions provide confidence on the model's ability to capture the main aspects of the site response at HVSC, despite..."

Reply: Accepted.

36. P10, L207-208. These differences could be adjusted for if necessary, though not a critical aspect.

Reply: Agreed.

37. P11, L217-218. What is the limited range of frequencies?

Reply: Here we actually meant to say that the site effect doesn't affect the low frequency motions. To clarify, we modified "Considering the fact that ... range of frequencies, ..." to "Considering that the site effects at HVSC would not affect ground motions of wavelengths much larger than the basin depth, ..."

38. P11, L221. Consider changing to "...motions. Because..."

Reply: Accepted.

39. P11, L225. The end of this paragraph comes across as inconclusive.

Reply: This paragraph is now rewritten.

40. P11, L226. Consider shortening the title to simply "Fourier amplitude spectral ratios"

Reply: Accepted.

41. P11, L238. The use of "somewhat" seems a bit informal and perhaps unnecessary.

Reply: Accepted.

42. P12, L242-247. In the interpretation of results given in the sentence "This suggests... surface ground motions", I would offer a different perspective perhaps the authors would like to comment on. For me, the results in question here indicate that the simulations do not have the level of variability observed in the records at the low frequencies. Then in the subsequent sentence "Interestingly,... numerical simulations." I would also suggest noting that the fact that this "uncertainty" is indeed seen in the synthetics may be indicative that the nonlinear behavior of the shallower profile in the simulations is contributing to increasing the variability. Did the

authors observed changes in the overall variability of simulations when assuming linear elastic conditions?

Reply: Yes we agree that the simulations do not have the same level of variability, and we believe that the reviewers' interpretation is the same as ours. We believe the reasons for that are our simplistic assumptions and uncertainties on characterizing the base input motion (assumption of vertical incidence, simple amplitude correction based on Rrup, potential errors in source location, etc.)

With the linear elastic simulations, the variability (expected from the tolerance of the numerical scheme) is negligible in the entire frequency band considered, and therefore the result suggests that the variability of observed spectral ratios in higher frequencies is partially attributed to the soil non-linear response.

We modified the text to "Interestingly, the uncertainly of recorded spectral ratios is also larger in higher frequencies. This is consistent with the result of numerical simulations, which confirms that the soil non-linear response contributes to the variability of observed spectral ratios in high frequencies, f>3Hz."

43. P12, L251. I think it should be T > 0.2 s or 0.25 s, but definitely not 2 s. That would not be consistent with the Fourier amplitude spectral ratios, where the transition is seen at about 3 Hz. Here, 0.25 s would correspond to about 4 Hz, and that would make more sense.

Reply: We were trying to point out that the simulated and observed response spectra agree well in vibration periods that are not expected to be affected by the site effects which is really in the range of 1-2s.

44. P12, L258. I would add that this also suggests an improvement over the 3D results for periods below 1-2 s.

Reply: The last sentence is now rewritten to "... this clearly shows the benefit of explicitly modelling the near surface site response over the use of empirical predictions and 3D large scale ground motion simulations."

45. P12, L259. "The role of... in the ground motion" (?). I am actually not sure, but the way it is sounds a bit odd. Double check.

Reply: The section title is changed to "The 2D site effects on surface ground motion".

46. P12, L260-261. Consider rewording. "...have demonstrated that the complexity of the ground motion within sedimentary valleys increases because of wave interferences, which when constructive, may cause localized amplifications (Bard and..."

Reply: Accepted.

47. P13, L265. The comma is unnecessary.

Reply: Accepted.

48. P13, L269-271. Consider shortening to "...the basin edge and the Lyttelton rail portal, which further amplify...".

Reply: Accepted.

49. P13, L278. Add the value of the fundamental frequency, that is "...than the site fundamental frequency (~ 3 Hz)."

Reply: Accepted.

50. P13, L281. Should be "...exceeds the site's fundamental..."

Reply: Changed to "... the fundamental frequency of the site ..."

51. P14, L292-294. What is observed in Figure 15 is entirely consistent with what was observed from the Fourier spectral ratios. Could this figure be simply eliminated and mention that the comparison was made and the results led to consistent conclusions? I wonder if in fact, the paper could be shortened if the authors focus only on either response spectra or Fourier analysis. I mention this because all what is seen above or below 3-4 Hz is the same that is conversely seen below and above 0.25-0.3 s. (Although I understand that the subject of the paper is useful to both seismologists and engineers, and in that order people in each field tend to relate to one or the other.)

Reply: They might seem slightly redundant to some people, but we belive that it is benefitial to discuss both figures. The spectral ratio is the standard way of representing the site effects, which also shows in what frequeny amplification occurs. We find that comparing the 2D and 1D spectral ratios is useful in understanding the physics of how the 2D effect affects the ground motion differently (as in Figure 14).

On the other hand, SA is the metric most often used by the empirical models, and it is beneficial to have the direct comparison with empirical models.

52. P14, L306. Consider adding "...not yet obvious, other than what is expected from basin-depth effects."

Reply: Changed to "..., other than what is expected from the local 1D response."

53. P14, L307. Consider adding "become quite complex, and the basin-edge effects much more relevant."

Reply: Accepted.

54. P15, L312. Consider shortening the title to "Role of the soil constitutive models".

Reply: Accepted.

55. P15-P16. Here, again, it would be better to have a clearer description of the differences in the models. The discussion is very interesting but it is somewhat in abstract because the authors do not quite show the models but simply their effects on the results. It is obvious they have an effect but it is difficult to understand the implications without a better description of the details. I would also suggest a third section on the sensibility of the model to uncertainty in the material properties. That is, what if the parameters in the nonlinear (or even in the linear) constitutive models (or simply material properties) change? What is the effect this has on the simulation results and how they reflect on the level of "similarity" or "agreement" to which the authors referred earlier?

Reply: We slightly modified the sentences as follows, to help clarify the differences of the models:

"To demonstrate the effect of the soil hysteretic response due to such strong ground shaking, we performed the same analysis with the plasticity disabled within the PDMY model. Figure 18 and 19 show the comparisons of simulated HVSC acceleration time series and response spectra using the linear elastic and the non-linear soil."

"To ensure the two different models are equivalent, we chose to use the time-averaged shear wave velocity (i.e. wave travel time from end-to-end of soil elements is identical for both model; also the site fundamental frequencies are very similar) at HVSC, Vs=360m/s, for the pressure-independent model."

56. P16, L348-349. I am not sure about "as equivalent as possible". They are or are not equivalent. But it is not clear to me how one can measure levels of equivalency here. Not critical, just a thought.

Reply: Changed to "equivalent". They have equivalent travel time. And they do have very similar fundamental model frequency.

57. P17, L368. Delete double dot.

Reply: Accepted.

58. P17, L369. Rephrase to eliminate "abundance" as that was not a critical part of this study.

Reply: We respectfully disagree with the reviewer's recommendation in this regard. We believe that stressing the abundance of the data is important because of the high uncertainty in the estimated bedrock motions, that cannot be characterized unless sufficient number of recorded motions are used.

We therefore added the folowing as the third paragraph of the conclusion section: "However, estimating the bedrock motion from a nearby surface station (LPCC) appears to introduce significant uncertainty that is event-dependent. Our validation excercise suggests that it was necessary to quantify the level of such uncertainty by use of multiple recorded events, to understand how much the simplistic model can over- or under-estimate the ground motion intensities."

59. P17, L371. I think to say "replicate" is a little too much. I would suggest the authors limit their description to the ability of the model to produce comparable results that can help understand and explain observations, and the relevance of the different factors influencing site response in the valley.

Reply: Replaced by "simulate".

60. P17, L376, L378. Add "in low frequencies, f < 2 Hz" as you did for the previous sentence about the high frequencies.

Reply: Accepted.

61. P18-P21. Consistently capitalize (or rather not) the titles of articles.

Reply: Accepted.

62. P18, L401. Should be "The seismic..."

Reply: Accepted.

63. P18, L402. Should be "SH" and not "Sh".

Reply: Accepted.

64. P19, L416. "and"

Reply: Accepted.

65. P20, L442. Delete extra space before colon.

Reply: Accepted.

66. P20, L444-445. Delete extra spaces in "Mw 6.2"

Reply: Accepted.

67. P20, L456. Delete "eng," (I assume is a typo).

Reply: Accepted.

68. P21, L464. Are the quotation marks necessary? If not, please eliminate.

Reply: Accepted.

69. P21, L475. Delete "en," (I assume is a typo).

Reply: Accepted.

70. P29-30. Consider merging these two figures into one where the inset covers a slightly larger area to include the stations. (Arguably, the article has too many figures.)

Reply: We acknowledge the reviewer's point. However, we believe that merging these two would not be feasible, because one is showing the epicentres of all earthquakes and the overview of the location, and another is presenting the qualitative representation of the site effects.

71. P33, Figure 5. Avoid nested parenthesis in figure caption and change to "Modified".

Reply: Accepted.

72. P37, Figure 9. As mentioned before, (c) and (d) are very similar, consider using a different event that could, perhaps, exemplify the response to near but weak events.

Reply: As discussed in comment 34, although this sounds intriguing, we would argue that we would gain little insight by this because of aforementioned practical challenges.

73. For all figures showing Fourier spectral ratios, and for all figures with response spectra or response spectrum residuals, the following comment. The maximum limit in the frequency axes should be consistent with the maximum frequency of the simulation for which the model is thought to be accurate. Most spectral ratio figures have an upper limit of 10 Hz, but figures 11 and 14, for instance, go up to 25-30 Hz. Hypothetically speaking, if the maximum frequency of the model is 10 Hz, then anything above that value is numerical noise and should not be shown in figures, or used for the analysis and discussion. Conversely, if the upper limit in frequency is 10 Hz, then the minimum period would be 0.1 s. Therefore, amplitudes or residuals below 0.1 s

would be the result of the response of an oscillator to numerical noise. Strictly speaking, one should not show response spectrum amplitudes at periods in the limit of the maximum frequency, because of the width of the SDOF transfer function. So, in the hypothetical case of fmax = 10 Hz, the minimum limit in the period axes should be about 0.125 s (corresponding to 8 Hz). Most figures have a lower limit in the period axis of 0.01 s. But there is no way we can trust the simulation results at such a low period, because it exceeds the corresponding maximum frequency (even if the results look OK.) Similarly, these simulations also have a minimum frequency. It depends on the size of the domain and the wave with the largest wavelength that can be propagated within the domain. Although this is not as critical an issue as I see it in regards to the maximum frequency, it would be best if the authors do a back-of-the-envelope calculation so that they can use a proper minimum value for the frequency axes, and a maximum value for the period axes in the figures with Fourier spectral ratios and spectral response (residuals), respectively. The point being that the limits in the horizontal axes of these different (Fourier and response) spectra figures should be (inversely) consistent with each other.

Reply: We agree with the reviewer that the frequency axis should be limited to the fmax that the model can handle. In fact, we would like to point out that all our plots are limited up to f=30Hz, and not 10Hz.

However, we respectfully disagree with the idea of limiting the frequency axis to a certain minimum frequency depending on the model dimension. If the frequency of the input motion is sufficiently low (i.e. wavelength much larger than the model size), then the model response would be close to the rigid body motion. Then the analysis result will show the input motion almost as is, which is not a bad thing. Rather, we believe that the limiting factor for the fmin would be the quality of the signal (sometimes the signals have strong low frequency noise so that they are not usable in some low frequencies). We also find that displaying the result in low frequencies (or in long periods) useful, because by doing so we can examine the suitability of our estimated input motions as they are not expected to be affected much by the model response.

We also do not necessarily agree that the frequency range of the spectral ratio and the period range of the response spectra needs to match because: 1) they serve different purposes, and 2) the frequency in the Fourier spectra and the vibration period in the response spectra are two different physical parameters. (For example, see **"On the Relationship between Fourier and Response Spectra: Implications for the Adjustment of Empirical Ground-Motion Prediction Equations (GMPEs)" by Bora et al, 2016**) Keeping that in mind, the reason why we limited the frequency of spectral ratio to 0.5Hz, rather than 0.1Hz(that is the inverse of 10s) is that it takes too much space without showing any important information (they just keep approaching unity).

Regarding the comment about the response spectra, we assume that the reviewer is assuming the amplitude of numerical noise woule be rather high beyond the fmax. However in our result, we did not see the significance of numerical noise beyond the fmax, probably because the fmax is already rather high and the recorded input motions do not have much energy near and beyond fmax. When there is no significant energy beyond fmax, then the response spectra for T<1/fmax is nearly flat because it is governed by the motion in lower frequencies. So, as long as there is no significant numerical noise beyond fmax, we don't see any harm in showing the SA in T<1/fmax, and it is customary to plot the SA in T=0.01-10s (e.g. Bradley 2015; Abrahamson and Silva 2008).

74. P42, Figure 14. Consider merging with Figure 11.

Reply: We acknowledge that this article has many figures. However, we wish to leave them as they are, because Figure 11 and 14 have their distinct purposes: one is for validation of the model, the other is for demonstration of 2D effects.

75. Figures 12, 15 and 21. Looking at these figures I think the black thick line should be the same in all three figures (median of the 2D simulations). That is indeed the case for Figures 15 and 21, but for some reason the black thick line in Figure 12 is slightly different. Why? Did I miss something? Double check, please.

Reply: We found that the Figure 12 was outdated. It is meant to be mean, not median. The figure is not updated.

Reviewer #2:

General comments :

- Mw to M(bold)

Reply: Accepted.

- I'd recommend describing the results in either frequency or period terms to avoid confusing the reader

Reply: While we agree that it will be neater if we can either use the Fourier spectra/spectral ratio or the response spectra, we strongly feel that they are complementary and serve their own purposes. For example, to have a direct comparison with empirical models use of SA is necessary. However, we can obtain little insights about how much and where the amplification occurs by looking at the SA only. We also presented some relevant discussions in our response to comment 73 of reviewer #1.

Specific comments :

- Line 6 : "..on the dynamic response…" of the dynamic response

Reply: Accepted.

- Line 10: "…reducing the spectral acceleration prediction bias by a factor of two in short vibration periods". Although the results support the statement, I haven't seen any further discussion in the main sections or in the Conclusions.

Reply: The relevant paragraph in the main text is rephrased as follows: "Despite the relatively large variability, the mean residual overall lies closer to zero and is much smaller than both the empirical model (Figure 5) and the large scale physics-based ground motion simulation with an empirical site amplification model (Figure 6), reducing the prediction bias by a factor of two in short vibration periods (T<0.3s). This clearly shows the benefit of explicitly modelling the near surface site response, over the use of empirical predictions and 3D large scale ground motion simulations."

The second paragraph of the conclusions is now changed to "With the aid of a detailed site characterization study and the abundance of recorded ground motion data during the 2010-2011

Canterbury earthquake sequence, our numerical model was able to simulate the observed site response reasonably well. In particular, the site-specific simulations performed significantly better than both empirical ground motion models and physics-based 3D regional scale ground motion simulations (which empirically accounts for the site effects). This suggests that carefully performed site-specific response simulations may be used where needed, to overcome the limitations of empirical ground motion models and regional-scale ground motions simulations."

- Line 13 and/or anywhere else in the manuscript: I think it will facilitate the comparisons presented later in the manuscript if the authors state the frequency range that they consider as high-frequencies (the frequency part the surface waves contribute significantly to ground motion).

Reply: Accepted. Changed to "... to the observed high frequency (f>3Hz) amplification ..."

- Line 78 and Figure 3: Add the magnitudes of these 3 events

Reply: Accepted.

- Equation 1: Describe all the right hand terms of the equation

Reply: Accepted. Added the follwing sentences: " The between-event residual is then further separated into the systematic event location-to-location residual, $\delta L2L_l$, and the remaining between-event residual, δB_{el}^0. Similarly, the within-event residual is separated into the systematic site-to-site residual, $\delta S2S_s$, and the remaining within-event residual, δW_{es}^0."

- Lines 121-134 : Describe in more detail Figure 6. What are the grey lines and which earthquake set they represent? The residuals (each grey line) are for the HVSC site or for all sites?

Reply: The text is now rephrased into "... (compared with the empirical prediction from Figure 5a, that used the same 10 recorded events) ..."

Also, the caption for Figure 6 is changed into "Spectral acceleration residuals of HVSC based on the ground motion simulations of Razafindrakoto et al. (2016), for the same 10 events used in Figure 5. Thin lines represent the residuals for the individual events."

- Line 145 : I think another figure (7b or 8b), showing in greater detail the cross-section used in the simulations should be added.

Reply: Thank you for the suggestion. We agree that accepting this suggestion would help readers. Assuming that the reviewer is suggesting to better describe how the velocity varies within the cross section, we modified Figure 8, such that it now clearly shows the boundaries of materials as described in Table 1.

- Line 158 : Add the abbreviation of the Pressure Dependent Multi Yield (PDMY) term here, since it's used later in the manuscript.

Reply: Accepted.

- Line 163 : Have the authors considered a velocity gradient for the volcanics?

Reply: We acknowledge that the actual Vs of the rock would vary with depth. However, we did not feel that we have sufficient data to come up with better model, and therefore we decided to use a constant Vs for each layer.

- Line 177, Table 2: I suggest to add the cross-symbol to the LPCC PGA and PGV headers as well. As it is now, it may confuse readers who will see only the table caption without reading the corresponding part in the manuscript that the fault-normal horizontal component is used only for HVSC recordings.

Reply: Accepted.

- Lines 185-186: Although it's not strictly within the scope of this publication, I would suggest to include a short paragraph and possibly an example figure to explain the deconvolution process for the LPCC site.

Reply: We accepted this suggestion and elaborated the sentence as follows: "The recorded motions from LPCC are then converted to the bedrock motion via deconvolution from its 1D elastic site response, which is done by simply dividing the Fourier transform of LPCC motion by the Thomson-Haskell transfer matrix (Haskell, 1953) and subsequently inverse-transforming back to the time domain."

However, especially considering the paper is already lengthy with lots of figures, we feel that adding additional figure is not necessary and hope that the additional information mentioned above would be sufficient.

- Line 246 : "uncertainly" uncertainty

Reply: Accepted.

- Line 293 : Both 1D and 2D underestimate the Sa at short periods. The authors probably want to stress that 1D results underestimate more than the 2D ones at this period range.

Reply: The paragraph is edited as follows: "The 2D effects are also evident in Figure 15, which shows the spectral acceleration residuals for the two different models. While it is apparent that both 1D and 2D models underestimate the spectral accelerations in short periods (T<0.3s), 2D simulations give overall lower residuals as expected."

- Lines 302 - 311: The authors state that in their results basin effects are practically negligible at periods longer than 0.8s. As it is shown in Figure 7, the Z1.5 is about 400m so it's not a very deep basin and the basin effects at longer periods are not expected to be very strong. There are however studies (empirical and theoretical) such as the Day et al. (2008) that predict basin effects at such shallow basins. What do the present study results mean with respect to the specific 2D implementation of the FE method and/or the parameters selected for modelling the soil response? I believe a short discussion addressing this issue should be included in the manuscript.

Reply: In the paper by Day et al. (2008), they discuss the source-averaged basin response factor (B factor) that has higher than 1 for Z1.5=300m and 500m.

In our study, the basin effects prevail in short vibration periods (T<0.3s), shorter than the fundamental period of the shallow basin. We believe that there was a slight confusion in terms of the Z1.5; Z1.5 is more like 60metres at the deepest part of the 2D model considered in this study (see Figure20a), and that is why our model do not show strong basin effects in long periods.

Amplification of strong ground motions at Heathcote Valley during the 2010-2011 Canterbury earthquakes: The role of 2D non-linear site response

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Abstract

This article presents a quantitative case study on the site amplification effect observed at Heathcote Valley, New Zealand, during the 2010-2011 Canterbury earthquake sequence for 10 events that produced notable ground acceleration amplitudes up to 1.4g and 2.2g in the horizontal and vertical directions, respectively. We performed finite element analyses of the dynamic response of the valley, accounting for the realistic basin geometry and the soil non-linear response. The site-specific simulations performed significantly better than both empirical ground motion models and physics based regional-scale ground motion simulations (which empirically accounts for the site effects), reducing the spectral acceleration prediction bias by a factor of two in short vibration periods. However, our validation exercise demonstrated that it was necessary to quantify the level of uncertainty in the estimated bedrock motion using multiple recorded events, to understand how much the simplistic model can over- or under-estimate the ground motion intensities. Inferences from the analyses suggest that the Rayleigh waves generated near the basin edge contributed significantly to the observed high frequency ($f > 3Hz$) amplification, in addition to the amplification caused by the strong soil-rock impedance contrast at the site fundamental frequency. Models with and without considering soil non-linear response illustrate, as expected, that the linear elastic assumption severely overestimates ground motions in high frequencies for strong earthquakes, especially when the contribution of basin edge-generated Rayleigh waves becomes significant. Our analyses also demonstrate that the effect of pressure-dependent soil velocities on the high frequency ground motions is as significant as the amplification caused by the basin edge-generated Rayleigh waves.

Keywords: Site effect, Basin edge effect, Amplification, Ground motion, Heathcote Valley, Canterbury earthquakes

Introduction

The strong motion station at Heathcote Valley primary school (HVSC) produced an extremely large acceleration time series during the February 2011 Christchurch earthquake, where the recorded peak acceleration reached $1.4g$ in the horizontal component and $2.2g$ in the vertical component (Bradley and Cubrinovski, 2011; Fry et al., 2011; Kaiser et al., 2012). The high intensity of this ground motion record may be attributed in part to the proximity of the earthquake source, as the source-to-site distance, R_{rup}, was only 3.9km, based on the finite fault model of Beavan et al., (2012). Nevertheless, the peak accelerations may still be considered unusually high given the relatively moderate earthquake magnitude of $\mathbf{M}6.2$. More importantly, the recorded peak accelerations at HVSC were consistently higher than nearby stations throughout the sequence of earthquakes during 2010-2011, which suggests strong near surface site effects (Bradley, 2015; Bradley and Cubrinovski, 2011). Bradley, (2015) furthermore demonstrated that the recorded motions at HVSC have pseudo spectral acceleration (PSA) values systematically higher than empirical predictions at short vibration periods throughout the sequence of earthquakes.

Heathcote Valley, shown in Figure 1, is approximately 10km away to the south-east from the central business district of Christchurch, located near the northern end of the Port Hills ,where the depth to the volcanics is expected to be shallow (Brown and Weeber, 1992; Brown and Weeber, 1994). Based on the wave propagation theory, the large impedance contrast resulting from shallow soft soils overlying the competent Port Hills volcanics may cause strong amplification of ground motion amplitude in high frequencies which may have contributed in part to the observed amplification in PGAs and short period PSAs.

In addition to the wave amplification caused by the strong impedance contrast based on the simple one-dimensional (1D) wave propagation theory, previous studies (Bradley and Cubrinovski, 2011; Bradley, 2012; Bradley and Baker, 2015) have also speculated that the ground motions at Heathcote Valley may be strongly amplified due to the surface waves generated at the non-planar soil-rock interface near the basin edge (Bard and Bouchon, 1980b; Kawase, 1996; Bard and Bouchon, 1980a).

Motivated by the aforementioned observation, and in order to better understand and quantify the principal physical phenomena resulting in the consistently large recorded ground motions, this study presents the result of site-specific response simulations of Heathcote Valley, accounting for the non-linear soil response and the realistic basin geometry. We synthesized detailed site investigation data comprising pre-existing data and recently performed geotechnical and geophysical testing to develop a realistic quantitative representation of the local geology of Heathcote Valley. Assuming two-dimensional (2D) plane strain conditions, dynamic finite element analyses are performed using OpenSees (McKenna, 2011), with deconvolved and amplitude-corrected ground motions recorded at the nearby Lyttelton Port Company station (LPCC) as input motions at the bedrock level. We demonstrate the performance and limitations of the model by comparing the numerical simulations with recorded ground motions at the station HVSC, in terms of acceleration time series and the acceleration response spectra. Based on the result of numerical simulations, we provide detailed discussions on the prominent roles of the shallow basin geometry, soil non-linear response, and pressure-dependent dynamic soil properties on the observed amplification of high frequency ground motions.

Observational evidence site effects at Heathcote Valley

Comparison of recorded motions: HVSC vs nearby stations

Figure 2 shows the East-West component acceleration time series recorded at HVSC, which demonstrates that ground motion recorded at this station during the September 2010 Darfield earthquake had significantly larger acceleration compared with nearby stations. Recorded motions of subsequent earthquakes at HVSC revealed that this observation was not limited to the 2010 September event alone. Throughout the sequence of earthquakes, there was a general tendency that the recorded motions at HVSC have acceleration amplitudes larger than the nearby stations. For example, Figure 3 shows the comparison of acceleration time series (horizontal fault-normal and vertical components) recorded at HVSC and LPCC, a nearby rock station, for three earthquakes: **M**7.1 04/09/2010, **M**6.2 22/02/2011, and **M**6.0 13/06/2011, which clearly demonstrates the large acceleration amplitudes observed at HVSC in both the horizontal (fault-normal) and vertical directions.

Amplification and mode-conversion caused by shallow inclined valley geometry

During the 2010-2011 Canterbury earthquake sequence, the HVSC strong motion station recorded a number of ground motions that show direct evidence of important 2D/3D site response. Figure 4 shows an example of how the recorded ground motion is affected by the 2D/3D site response for one of the aftershocks at 15 September 2010 (GeoNet public ID 3372561, see the Data and Resources section). In particular, this figure shows that the recorded vertical motion at HVSC has S-waves as intense as the horizontal motion, whereas the recorded vertical motion at LPCC has negligible contribution from the S-wave. The lack of S-wave contribution in vertical motion at LPCC suggests near vertical propagation of incident seismic waves; it is expected that the wave propagation at HVSC would have been also nearly vertical at the bedrock level, as the two stations are only 3km apart from each other and the earthquake source is more than 15km away from both stations towards the west. Therefore, the high amplitude of S-wave in the vertical motion at HVSC strongly suggests the refraction and mode-conversion of waves at the inclined soil-rock interface of the valley. Previous studies (Bard and Bouchon, 1980a; Bard and Bouchon, 1980b; Kawase, 1996) have shown that such phenomenon mostly occurs near the edge of the valley and generates surface waves, which can amplify the seismic motion within the valley through constructive interference.

Comparison with empirical predictions

Considering that the local geology of Heathcote Valley is characterized by a thin layer of soil over the Port Hills volcanic bedrock, it is expected that the dynamic response of this shallow soil layer would greatly amplify ground motions at high frequencies. Moreover, as speculated by Bradley and Cubrinovski, (2011), further amplification of the ground motions is likely due to the surface waves generated at the inclined soil-rock interface.

Taking advantage of the abundance of recorded earthquakes during the 2010-2011 Canterbury earthquake sequence, Bradley, (2015) demonstrated the systematic site effects of 20 strong motion stations, including HVSC, by relaxing the conventional ergodic assumption (Anderson and Brune, 1999). In that study, the non-ergodic empirical ground motion is expressed as:

$$\begin{aligned} lnSA_{es} &= f_{es}(Site, Rup) + \delta B_e + \delta W_{es} \\ &= f_{es}(Site, Rup) + (\delta L2L_l + \delta B^0_{el}) + (\delta S2S_s + \delta W^0_{es}), \end{aligned} \tag{1}$$

where $lnSA_{es}$ is the natural logarithm of the observed spectral acceleration (SA), and the first, second, and third terms on the right hand side represent the mean prediction of SA, the between-event residual, and the within-event residual, respectively. The between-event residual is then further separated into the systematic event location-to-location residual, $\delta L2L_l$, and the remaining between-event residual, δB^0_{el}. Similarly, the within-event residual is separated into the systematic site-to-site residual, $\delta S2S_s$, and the remaining within-event residual, δW^0_{es}.

Figure 5 shows the within-event residuals, δW_{es} for 10 different earthquake events and the systematic site-to-site residual, $\delta S2S_S$ (the mean of δW_{es}, which represents the site-specific effects), of both HVSC (Figure 5a) and all 20 stations (Figure 5b) for all events considered. The site-to-site residual at HVSC clearly demonstrates the amplification at vibration period $T < 0.5s$ specific at this station that is significantly greater than the empirical prediction.

Comparison with broadband ground motion simulations

Razafindrakoto et al., (2016) performed a series of regional-scale ground motion simulations for the Canterbury region during the 2010-2011 Canterbury earthquake sequence, using the hybrid broadband simulation methodology developed by Graves and Pitarka, (2015). Taking advantage of a recently developed 3D crustal velocity model of Canterbury region (Lee et al., 2016), their simulations of the ground motion amplitude residuals, depicted in Figure 6, show a significant reduction (compared with the empirical prediction from Figure 5a, that used the same 10 recorded events) of the spectral acceleration residuals at long periods (i.e. $T > 1s$), whereas there is still a significant bias at short vibration periods. In this regard it can be noted that the explicit consideration of a 3D crustal model and wave propagation physics leads to an improvement for the low frequency ($f < 1Hz$) portion of the hybrid simulation. The high frequency ($f > 1Hz$) portion of the hybrid simulation, which uses a simplified physics-based approach (Graves and Pitarka, 2010; Graves and Pitarka, 2015) and, in particular, the empirical site effect model of Campbell and Bozorgnia, (2014), produces biased predictions similar to those of the empirical ground motion model of Bradley, (2013).

2D site response simulation

Model description

Motivated by the previously discussed observations, and inability of two conventional ground motion modelling approaches to adequately capture high frequency amplitudes observed at the HVSC station, we performed a series of two-dimensional non-linear dynamic finite element analysis, to examine the role of shallow geological conditions on the surface ground motions at Heathcote Valley. Fifteen seismic cone penetration tests (sCPT) and 26 single-sensor ambient vibration tests are conducted to characterize the shear wave velocity and the thickness of sedimentary soils. Figure 7 and Table 1 summarize the results of the aforementioned site-characterization study; the details are summarized in (Jeong and Bradley, 2016). Figure 7 shows fence diagrams of the cross-sections of 3D shear wave velocity model of Heathcote Valley based on the geophysical tests, in which the cross section considered in the 2D analyses is marked as 'N75E'.

Figure 8 shows the two dimensional mesh geometry, created with the pre/post processor GiD (see the Data and Resources section) for the valley cross section (along the bearing of N75E). The model comprises 24866 four-node quadrilateral elements, in which the target element size is two metres for soil and five metres for rock. In the soil domain we target four elements per wavelength, that is eight integration points per wavelength. The minimum wavelength is then eight metres, and therefore the maximum frequency is at least 25Hz.

The non-reflective boundary condition at the base of the model is implemented by employing viscous dashpots (Lysmer and Kuhlemeyer, 1969), in which the dashpot coefficients are calculated using

$$C = \rho V_S A, \tag{2}$$

where ρ is the mass density, V_S is the shear wave velocity, and A is the tributary length of element sides facing the bottom boundary and sharing each boundary node. The periodic boundary condition is imposed on the lateral boundaries, after extending the computational domain by 600 metres on each side. The incident waves are assumed to propagate vertically as plane waves which are then modelled as equivalent nodal forces using the following equation:

$$p = \rho V_S A \dot{u}, \tag{3}$$

where $\dot{u}$ is the bedrock input velocity. The dynamic constitutive behaviour of Port Hills loess is modelled by the Pressure Dependent Multi Yield (PDMY) plasticity model (Yang et al., 2003), which assumes a power-law dependency of the shear modulus to the soil effective stress.

For simulating the response of dry soils with the PDMY model, the only necessary parameters are the initial modulus (or velocity) that is function of effective stress (or depth), friction angle that defines the strength, and a shear modulus degradation curve that defines how stress-strain curve varies with strain. We used the default option for the degradation curve, which is called the modified hyperbolic model (Kondner, 1963). The model also requires some other parametres for simulating the effect of pore water pressure. However these parametres are irrelevant for this study and therefore some recommended (by the model developers, see the website in the Data and Resources section) values are used.

In the model, the velocity of soil is then represented by a power law equation which were obtained by a regression analysis of the measured velocities:

$$V_S = 207z^{0.25}, \tag{4}$$

where z is the depth from the ground surface. The constitutive behaviour of the underlying Port Hills volcanics is modelled with a linear elastic material which adopts the shear wave velocity published by Wood et al., (2011). We acknowledge that the actual wave velocity of the rock would be a lot more variable For all materials, the Poisson's ratios are assumed as $\nu = 0.25$, and the ground water was not considered. Table 1 summarizes the key parameters used in the simulations, and the detailed information on the geophysical investigations can be found in Jeong and Bradley, (2016).

As a requirement for the PDMY model, the analysis is performed in multiple stages. Because the PDMY model requires the at-rest confining stress as the initial condition for the dynamic analysis, we first perform a linear-elastic gravity analysis with the bottom boundaries fixed. After the linear-elastic gravity analysis is done, we then perform the gravity analysis with soil plasticity enabled, which will update the stress field to be compatible with the soil plasticity model. After the plastic gravity analysis, we release the fixities of the bottom boundaries and apply the computed gravity reactions on the boundary nodes to satisfy the static equilibrium. This step is required to implement the absorbing boundary condition and equivalent force input motion. For time integration, we used the implicit

Newmark-beta method, which is unconditionally stable, with $\Delta t = 0.005s$ and the number of time steps of 16384 for the total duration of about 80 seconds.

There are two different mechanisms of attenuation in the model: the hysteretic damping caused by plastic yielding of soils, and the visco-elastic attenuation which is modelled with a stiffness proportional global damping matrix, that has no damping at $f = 0Hz$, and 1% of critical damping at $f = 15Hz$, linearly varying in frequency.

Earthquake events selected for the simulation

GeoNet, New Zealand geological hazard monitoring network, recorded a large set of strong ground motions during the 2010-2011 Canterbury earthquake sequence, which include four major earthquakes with magnitude $\mathbf{M} \geq 5.9$ and more than 300 aftershocks of $M_L > 4.0$. This study utilizes recorded ground motions of ten selected earthquakes listed in Table 2 in chronological order, which also shows moment magnitudes ($\mathbf{M}$), source-to-site distances (R_{rup}), peak ground accelerations (PGA), and peak ground velocities (PGV) recorded at stations HVSC and LPCC for each event. The selected earthquake events have moment magnitudes $\mathbf{M}4.7$ to $\mathbf{M}7.1$, and produced significant ground motions in the urban Christchurch area (and thus have good signal-to-noise ratios). In Table 2, both PGA and PGV are for the horizontal fault-normal component, and R_{rup} is the shortest distance from the station to the fault rupture surface, where the source-to-site distances R_{rup} are calculated based on the finite fault models by Beavan et al., (2012) for the four largest events (04/09/2010, 22/02/2011, 13/06/2011b, 23/12/2011b), and based on simplified approximations of the finite faults for the smaller events (Bradley, 2015).

With the absence of a borehole station at the bedrock level, we chose to use the recorded motions at LPCC, which is located at the Lyttelton Port approximately 3 kilometres away from Heathcote Valley (see Figure 1) on the volcanic rock ($V_S = 1500m/s$) that underlies shallow surficial soils (Wood et al., 2011). The recorded LPCC motions are rotated to the azimuth of 75 degrees, as the two stations are relatively close to each other and the 2D model of Heathcote Valley is along that azimuth. The recorded motions from LPCC are then converted to the bedrock motion via deconvolution from its 1D elastic site response, which is done by simply dividing the Fourier transform of LPCC motion by the Thomson-Haskell transfer matrix (Haskell, 1953) and subsequently inverse-transforming back to the time domain. The amplitudes of the deconvolved motions are then corrected to account for the differences in the source-to-site distances between HVSC and LPCC, using a New Zealand-specific empirical ground motion model (Bradley, 2013).

Validation of 2D site response model

Numerical simulations are validated by comparing the acceleration time series, HVSC/LPCC spectral ratio, and acceleration response spectra of simulated and recorded ground motions for the ten earthquake events listed in Table 2.

Acceleration time series

Figure 9 shows simulated and recorded acceleration time series for the N75E component, for the four major earthquake events: **M**7.1 September 2010, **M**6.2 February 2011, **M**6.0 June 2011, and **M**5.9 December 2011. All time series shown in the Figure 9 start at the earthquake rupture origin time. Since we obtain the input motions from the recorded motions at LPCC, the differences in arrival time between recorded and simulated motions originates from the difference in arrival times at HVSC and LPCC as a result of different path effects.

Besides the possible limitations of the model itself (e.g. 2D approximation of a 3D problem, pore water pressure effects being ignored, and uncertainties in the constitutive parameters), it is expected that the simulated surface motions would be also affected by the uncertainties in the amplitude of the estimated input motions and the assumption of vertically incident waves (Bard and Bouchon, 1980b; Papageorgiou and Kim, 1993).

Nonetheless, the similarities between the simulated and recorded ground motions provide confidence on the model's ability to capture the main aspects of the site response at

HVSC, despite a number of simplifying assumptions of the model and the aforementioned uncertainties.

Acceleration response spectra

In addition to the comparison of acceleration time series, we also compared the simulated and recorded acceleration response spectra for the four major earthquakes as shown in Figure 10. Simulated response spectra overall agree well with observations, however it is clear in Figure 10d that the simulated response spectra of **M**5.9 December 2011 event is significantly overestimated in the entire period range. There were also a few other cases among the 10 events considered in this study, where the simulation either underestimates or overestimates the response spectra for the entire period range.

Considering that the site effects at HVSC would not affect ground motions of wavelengths much larger than the basin depth, it was evident that in some events (e.g. 23/12/2011b) the amplitude of estimated input motion is considerably different than the observation. The reason for this discrepancy is most likely associated with the aforementioned uncertainty in the amplitude of estimated input motions. Because the site response is expected to affect the surface ground motion only for a certain period range, ground motions at sufficiently long periods would not be affected by the shallow site response.

Therefore, if the amplitudes of input motions are properly estimated, the simulated and observed response spectra are expected to be very close to each other at long periods. However this was not the case for the December 2011 events and a few others, which demonstrates the importance of considering multiple earthquakes for validation of near surface site response models.

Fourier amplitude spectral ratio

Figure 11 shows the comparison of simulated and recorded Fourier spectral amplitude at HVSC, normalized by the recorded Fourier spectral amplitude at LPCC. Before computing the spectral ratios, Fourier amplitude spectra are smoothed using the method by Konno and Ohmachi, (1998) with the bandwidth coefficient $b = 40$. Because of the normalization with respect to the recorded LPCC motions that are being used as input motion through linear elastic deconvolution analysis, the HVSC/LPCC spectral ratio can provide more direct comparison of the shallow site response of Heathcote Valley. Figure 11 shows an excellent agreement of the median spectral ratios, where both the simulated and recorded spectral ratios show peak median amplification factors of four at the frequency, $f \sim 3Hz$. Considering the geology of Port Hills, the high impedance contrast between the near surface soils (loess) and the Port Hills volcanics would likely dominate such high amplification factor.

As expected, the standard deviations from simulated and recorded spectral ratios differ significantly. The standard deviations of the simulated spectral ratios are much larger in frequencies higher than the site fundamental frequency due to the soil non-linear response, and negligible in lower frequencies. However, spectral ratios from the recorded motions show a large uncertainty in the low frequencies as well. This suggest that even though our model assumption–using the LPCC recorded motions as input and assuming vertical incidence–may be appropriate on average, simulations of individual earthquake events with such assumptions may significantly under- or over-estimate the surface ground motions. Interestingly, the uncertainly of recorded spectral ratios is also larger in higher frequencies. This is consistent with the result of numerical simulations, which confirms that the soil non-linear response contributes to the variability of observed spectral ratios in high frequencies, $f > 3Hz$.

Response spectra prediction residuals

Figure 12 shows the residual of the response spectral acceleration, that is defined as:

$$r = log(SA_{Observed}) - log(SA_{Simulation}) \tag{5}$$

On average, the observed and simulated response spectra agree very well with each other at long vibration periods (i.e. $T > 2s$), albeit with a large uncertainty. We emphasize that the large uncertainty at long periods is most likely associated with input motion characterization uncertainty as discussed earlier, and this demonstrates the importance of considering a large number of earthquake events in the simulations. Despite the relatively large variability, the mean residual overall lies closer to zero and is much smaller than both the empirical model (Figure 5) and the large scale physics-based ground motion simulation with an empirical site amplification model (Figure 6), reducing the prediction bias by a factor of two in short vibration periods ($T < 0.3s$). This clearly shows the benefit of explicitly modelling the near surface site response, over the use of empirical predictions and 3D large scale ground motion simulations.

The 2D site effects on surface ground motion

A number of previous studies have demonstrated that the complexity of ground motion within the sedimentary valleys increases because of wave interferences, which when constructive, may cause localized amplifications (Bard and Bouchon, 1980a; Bard and Bouchon, 1980b; Kawase, 1996; Papageorgiou and Kim, 1993; Pedersen et al., 1995; Semblat et al., 2005). Figure 13 shows the snapshots of velocity vectors obtained from the simulation of the Heathcote Valley model with a Ricker wavelet of $f = 6Hz$ as an input motion. By comparing the amplitudes of velocity vectors before and after the wavelet enters the soft sediment layer (i.e. Figure 13a and Figure 13b), one can easily observe the effect of the impedance contrast on the amplification of ground motions. In addition, Figure 13c and onwards also show the Rayleigh waves generated near the basin edge and the Lyttelton rail portal, which further amplify the ground motion by interfering with incident and reflected waves.

2D vs 1D simulation at HVSC

To investigate the role of 2D site effects, we compared the HVSC/LPCC spectral ratios of 2D and 1D simulations as shown in Figure 14, where the 1D simulations are performed using the velocity profile evaluated at the location of the station HVSC (Jeong and Bradley, 2016). In both 1D and 2D spectral ratios, the fundamental frequencies and the corresponding peak amplitudes are quite similar. However, it is clear that the spectral amplitudes in 2D simulations are significantly higher at frequencies greater than the site fundamental frequency ($f_0 \approx 3Hz$). On the subject of the wave propagation problem of 2D sediment filled valleys subjected to SV waves, Bard and Bouchon, (1980b) have shown that the Rayleigh wave modes are excited as soon as the frequency of the incident motion exceeds the fundamental frequency of the site. As previously discussed, the steep cut slopes made near the Lyttelton rail tunnel is another source of Rayleigh waves. It is expected that those Rayleigh waves generated near the basin edge and the rail portal would have made a significant contribution to the high spectral ratio via interference with incident and reflected waves.

Somewhat unexpectedly, the spectral ratio of 1D model shows amplitude higher than the 2D model in lower frequencies (i.e. $f = 0.5 - 2Hz$ in Figure 14); it also shows higher amplitude than the median recorded spectral ratio. Considering the fact that such overestimation only occurs in lower frequencies where the soil response is expected to be small, the most logical explanation to this observation would be the topographic deamplification of ground motions, caused by the wave scattering due to the slight depression of the valley topography.

The 2D effects are also evident in Figure 15, which shows the spectral acceleration residuals for the two different models. While it is apparent that both 1D and 2D models underestimate the spectral accelerations in short periods ($T < 0.3s$), 2D simulations give overall lower residuals as expected.

2D effects as function of location along the valley surface

Discussions on the role of 2D site response so far have only focused on the ground motions at the location of the strong motion station HVSC. However, the amplification of ground motions caused by the basin effects are known to be location dependent (Kawase, 1996; Semblat et al., 2005; Bard and Bouchon, 1980a). To illustrate how the ground motion intensities vary along the valley surface, we plotted in Figure 16 the spectral accelerations, normalized with respect to the spectral accelerations of the input motions, along the valley surface for periods $T = 0.1$, 0.2, 0.4, and 0.8 s. As expected, it becomes immediately obvious that the basin effects become irrelevant as soon as the considered vibration period is long enough. At $T = 0.4s$, which is quite close to the site fundamental period, the maximum response seems to occur at the centre of the valley, and the effects of 2D response are not yet obvious, other than what is expected from the local 1D response. At short periods ($T = 0.1$ and 0.2 s), however, the spatial pattern of spectral accelerations become quite complex, and the basin edge effects much more relevant. For $T = 0.1s$, the median amplification of spectral accelerations are as high as three almost everywhere on the valley surface, whereas comparable level of amplifications are observed only near the center of the valley for $T = 0.4s$. Topographic amplification is also evident in $T = 0.1$ and 0.2 s, where peak amplification is observed near the crest of the steep cut slopes near the Lyttelton rail tunnel.

Role of the soil constitutive models

Hysteretic response of the soils

Soils exhibit a non-linear hysteretic stress-strain response when subjected to the strong shaking. This non-linear behaviour is known to affect the resulting amplitude and frequency content characteristics of surface ground motions significantly. Proper modelling of such response characteristics is therefore necessary for satisfactory prediction of the ground motion intensities.

Figure 17 shows the contours of simulated peak strains for the two strongest earthquake events: 22/02/2011 and 13/06/2011. Simulated ground strains for these earthquakes were particularly high, especially near the Lyttelton rail tunnel; the February earthquake also caused significant ground strain near bottom of the basin edge.

In soil mechanics, shear strain of 0.1% and above is considered large and known to cause significant hysteretic behaviour (Ishihara, 1996). It is therefore expected that such high ground strain and the associated hysteretic behaviour would significantly alter the characteristics of the ground motions. To demonstrate the effect of the soil hysteretic response due to such strong ground shaking, we performed the same analysis with the plasticity disabled within the PDMY model. Figure 18 and 19 show the comparisons of simulated HVSC acceleration time series and response spectra using the linear elastic and the non-linear soil model. Both in the time series and the response spectra, the reduction of the acceleration amplitude is evident for the non-linear simulation.

Pressure dependency

Granular soils such as the Port Hills loess considered in this study are known to have effective stress-dependent elastic moduli and strengths. Shear wave velocity data of the Port Hills loess obtained at Heathcote Valley–albeit with some level of variability–behave precisely in this manner, and our study have shown that the soil velocity can be modelled with a single power law equation as shown in equation (4). This means that the wave velocity of soils vary very rapidly near ground surface. However, the majority of studies on the wave propagation and site amplification problem have assumed simpler layer-wise homogeneous soils, and the effect of such rapid variation of wave velocity near the ground surface has not been thoroughly studied.

Motivated by the simulations performed with the PDMY soil model described previously, we conducted an additional set of simulations to investigate the appropriateness of the commonly assumed pressure independent (layer-wise homogeneous) constitutive laws. In this set of simulations, the PDMY soil model was replaced by the pressure-independent multi-yield (PIMY) plasticity model–a variant of PDMY model with a constant shear strength and modulus across the depth of the soils. Figure 20a shows the comparison of the shear wave velocity profiles of the two models. To ensure the two different models are equivalent, we chose to use the time-averaged shear wave velocity (i.e. wave travel time from end-to-end of soil elements is identical for both model; also the site fundamental frequencies are very similar) at HVSC, $V_S = 360m/s$, for the pressure-independent model. The shear strength of the pressure independent model is assumed to be $\tau_{max} = 150kPa$ as shown in Figure 20b, which is slightly higher than the average strength ($141kPa$) of the pressure dependent model. We then compared the SA residual of the pressure-dependent and pressure-independent model as in Figure 21, which clearly demonstrates the effect of the soil pressure dependency on the surface ground motions. The difference of the SA residual appears insignificant in the vibration periods $T > 0.5s$, where it might seem that the pressure independent model appears to perform satisfactorily. However, considering that the site amplification for $f < 2Hz$ is found to be negligible as shown in Figure 11, the more likely reason of similarity between the two models for $T > 0.5s$ is that the ground motions in this period range are less sensitive to the smaller length scale variations between the two modelling assumptions. The pressure-independent model results in much higher residuals at vibration periods $T < 0.5s$, suggesting that the pressure-independent soil model would significantly underestimate the site amplification for such vibration periods.

Conclusions

We presented a case study of the site amplification effect observed at Heathcote Valley, New Zealand, during the 2010-2011 Canterbury earthquake sequence using the recorded strong motion data and the result of numerical simulations of 10 earthquake events that produced notable ground motion amplitudes.

With the aid of a detailed site characterization study and the abundance of recorded ground motion data during the 2010-2011 Canterbury earthquake sequence, our numerical model was able to simulate the observed site response reasonably well. In particular, the site-specific simulations performed significantly better than both empirical ground motion models and physics-based 3D regional scale ground motion simulations (which empirically accounts for the site effects). This suggests that carefully performed site-specific response simulations may be used where needed, to overcome the limitations of empirical ground motion models and regional-scale ground motions simulations.

However, estimating the bedrock motion from a nearby surface station (LPCC) appears to introduce significant uncertainty that is event-dependent. Our validation exercise suggests that it was necessary to quantify the level of such uncertainty by use of multiple recorded events, to understand how much the simplistic model can over- or under-estimate the ground motion intensities.

By comparing the 2D simulations with a hypothetical equivalent 1D model, we demonstrated that the Rayleigh waves generated near the basin edge might have caused significant amplification in high frequencies, $f > 3Hz$, whereas the slightly depressed valley topography likely deamplified the ground motions in low frequencies, $f < 2Hz$.

Our simulations suggest that the maximum ground strain at Heathcote Valley might have exceeded $\gamma = 0.1\%$ for a few events during the earthquake sequence, and such high ground strain would have altered ground motion characteristics significantly. The assumption of linear-elastic soils for such intense ground shaking would certainly over-estimate ground motion intensities, especially when the contribution of the basin edge-generated, and subsequently trapped, surface waves becomes significant.

Finally, we showed through our simulations that the effective stress-dependent shear wave velocity of granular soils might have an impact, as significant as the 2D valley response, on the intensity of high frequency surface ground motions.

Data and Resources

Ground motion records are from GeoNet (http://www.geonet.org.nz). Simulations are performed with an open-source finite element analysis code, OpenSees (McKenna, 2011), using the PDMY soil plasticity model (http://www.soilquake.net/opensees/). The finite element mesh is generated using the GiD pre/post processor (http://www.gidhome.com). Figures are created using Matplotlib (Hunter, 2007) and the Generic Mapping Tool (Wessel et al., 2013).

Acknowledgements

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Table 1: Summary of material constitutive properties used for the analyses.

Material type	Shear wave velocity V_S $[m/s]$	Mass density ρ $[Mg/m^3]$	Poisson ratio ν	Friction angle ϕ $[°]$	Cohesion intercept c $[kPa]$
Soil (PDMY)	$207z^{0.25*}$	1.8	0.25	36	30
Rock1 (Linear Elastic)	800	2.4	0.25	-	-
Rock2 (Linear Elastic)	1500	2.4	0.25	-	-

* z is the depth from the surface

Table 2: Earthquake events used in the analyses, in chronological order.

		HVSC			LPCC		
Event date	**M**	R_{rup}* (km)	PGA† (g)	PGV† (cm/s)	R_{rup}* (km)	PGA† (g)	PGV† (cm/s)
04/09/2010	7.1	20.8	0.61	29	22.4	0.29	19
19/10/2010	4.8	12.8	0.09	3.2	13.1	0.02	0.71
26/12/2010	4.7	4.7	0.11	2.9	7.7	0.02	0.65
22/02/2011	6.2	3.9	1.41	81	7.0	0.92	46
16/04/2011	5.0	7.3	0.68	32	5.2	0.29	8.5
13/06/2011a	5.3	4.7	0.45	14	5.3	0.15	5.4
13/06/2011b	6.0	3.6	0.91	55	5.8	0.64	33
21/06/2011	5.2	14.9	0.26	8.0	15.6	0.07	2.1
23/12/2011a	5.8	9.9	0.31	12.7	11.4	0.24	7.6
23/12/2011b	5.9	9.7	0.44	22	12.4	0.44	23

* The shortest source-to-site distance based on Beavan et al., (2012)
† Horizontal fault-normal component

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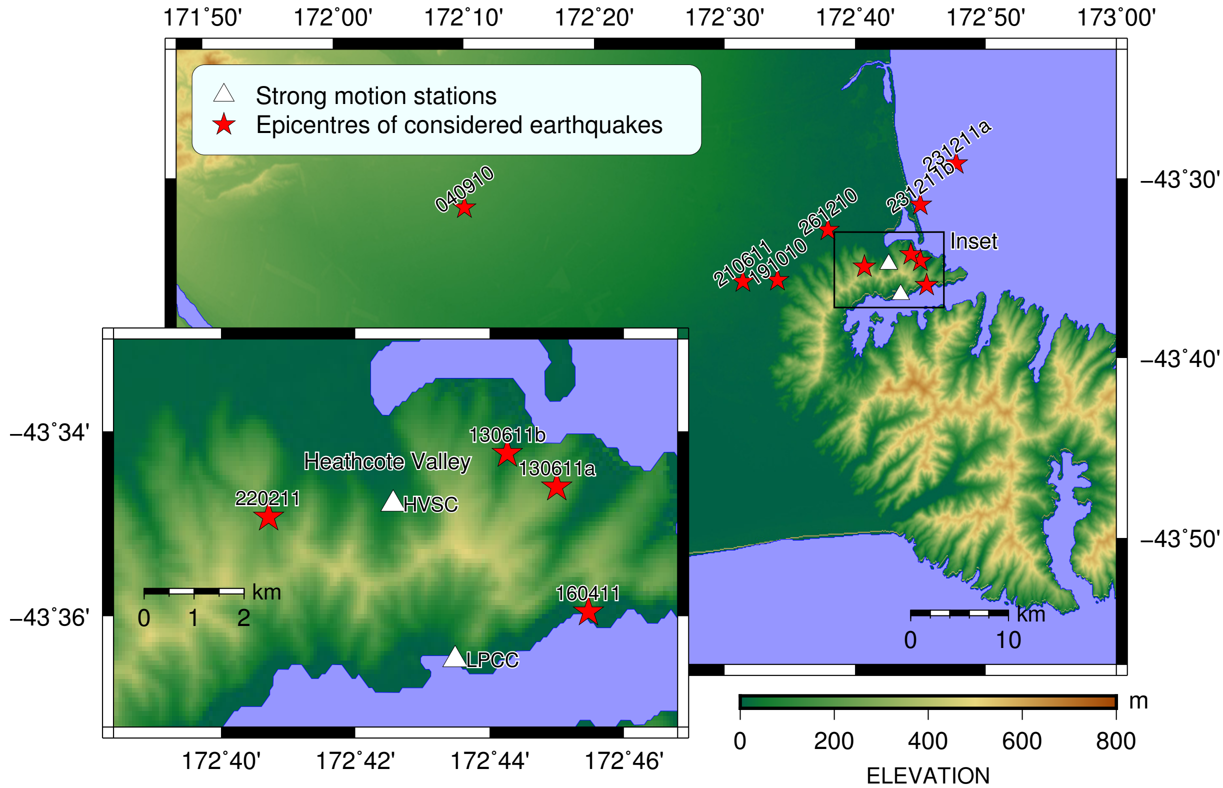


Figure 1: Locations of strong motion stations (HVSC and LPCC) and epicentres of the simulated events. The figure inset shows a close-up of Heathcote Valley and the surrounding area.

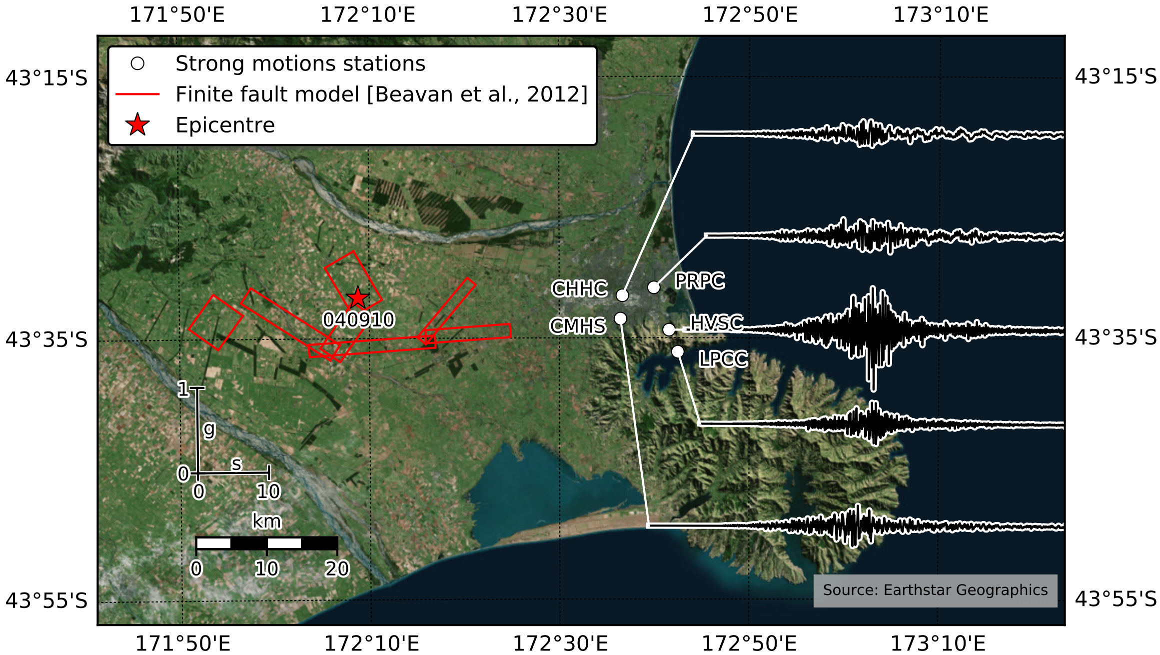
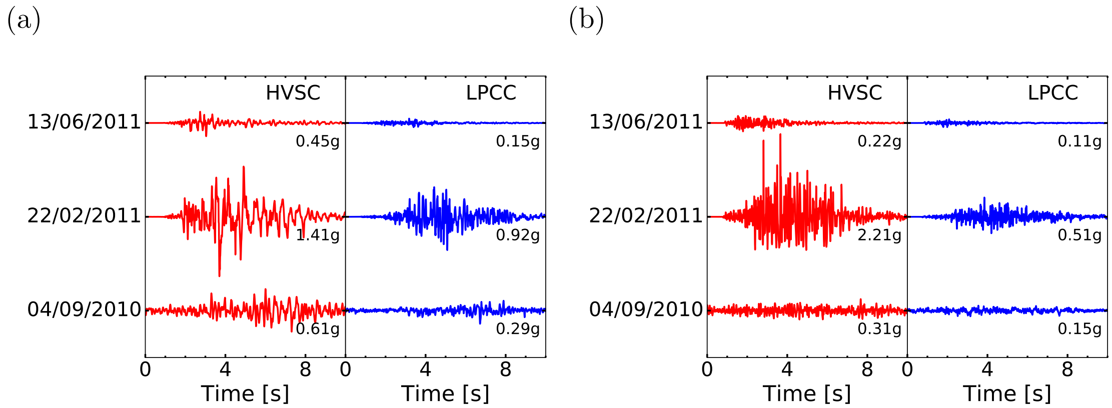


Figure 2: Example illustration of large amplitude ground motions at HVSC for the recorded east-west component acceleration time series for the **M**7.1 2010 Darfield earthquake (04/09/2010) at HVSC and four nearby strong motions stations.



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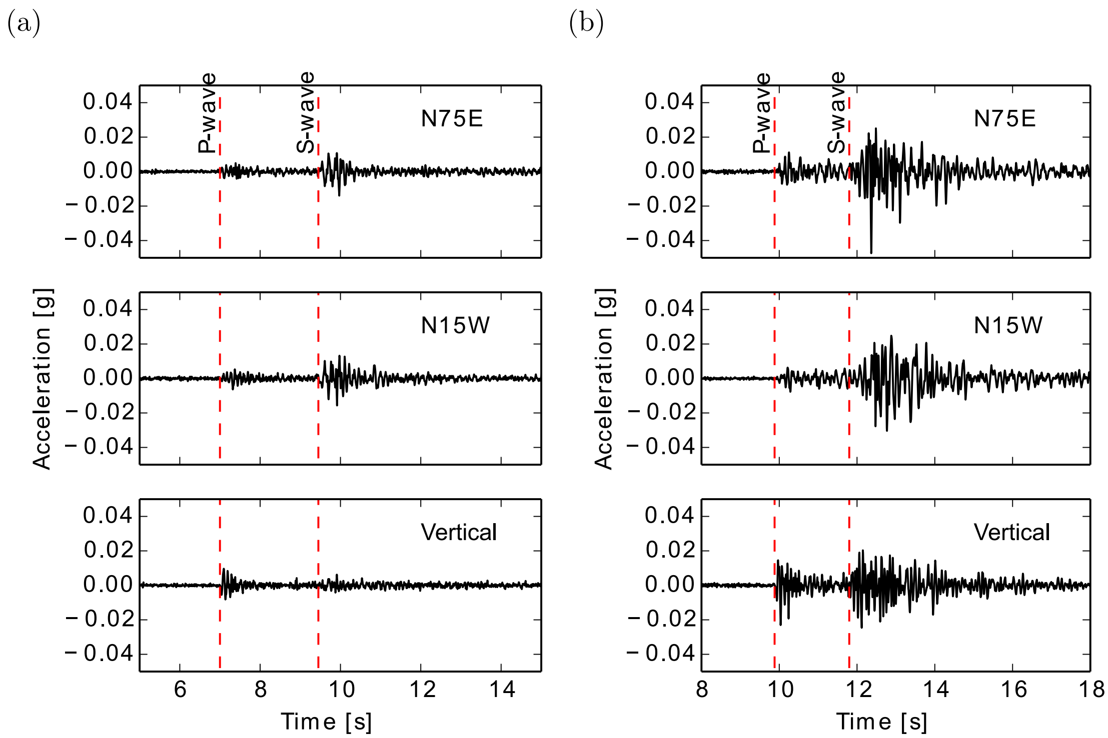

Figure 4: Recorded acceleration time series at (a) LPCC and (b) HVSC for an aftershock event (15/09/2010): the LPCC record indicates little contribution of refracted/mode-converted S-waves in the vertical component, whereas for the HVSC record such waves result in the vertical motion having an amplitude similar to the horizontal components.

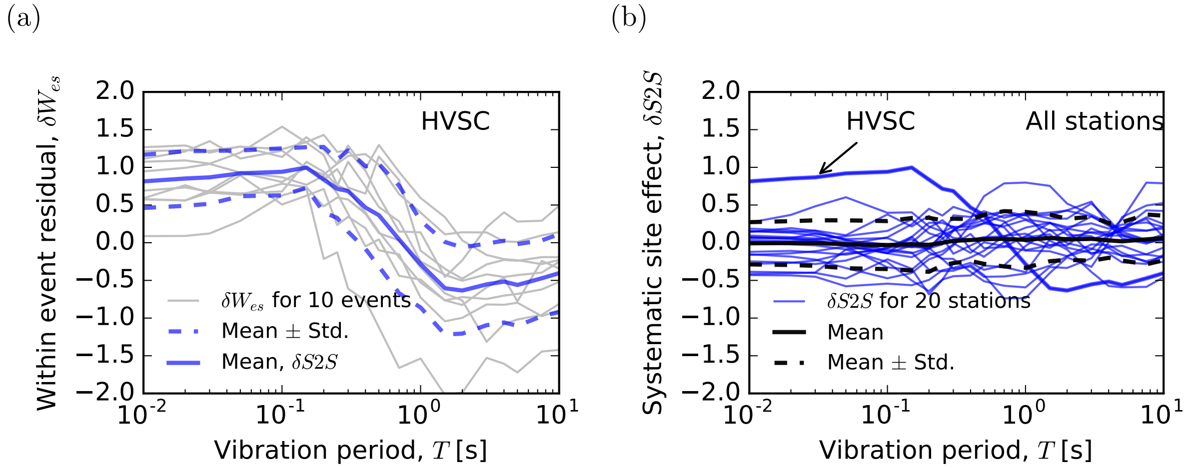

Figure 5: (a) Within-event residuals for individual events, and the site specific effect, $\delta S2S$ at HVSC; and (b) $\delta S2S$ for all 20 stations in urban Christchurch, modified from Bradley, (2015)

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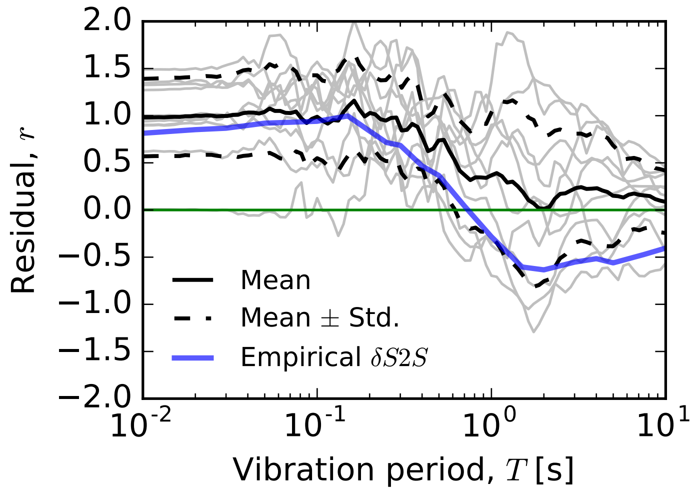


Figure 6: Spectral acceleration residuals of HVSC based on the ground motion simulations of Razafindrakoto et al., (2016), for the same 10 events used in Figure 5. Thin lines represent the residuals for the individual events

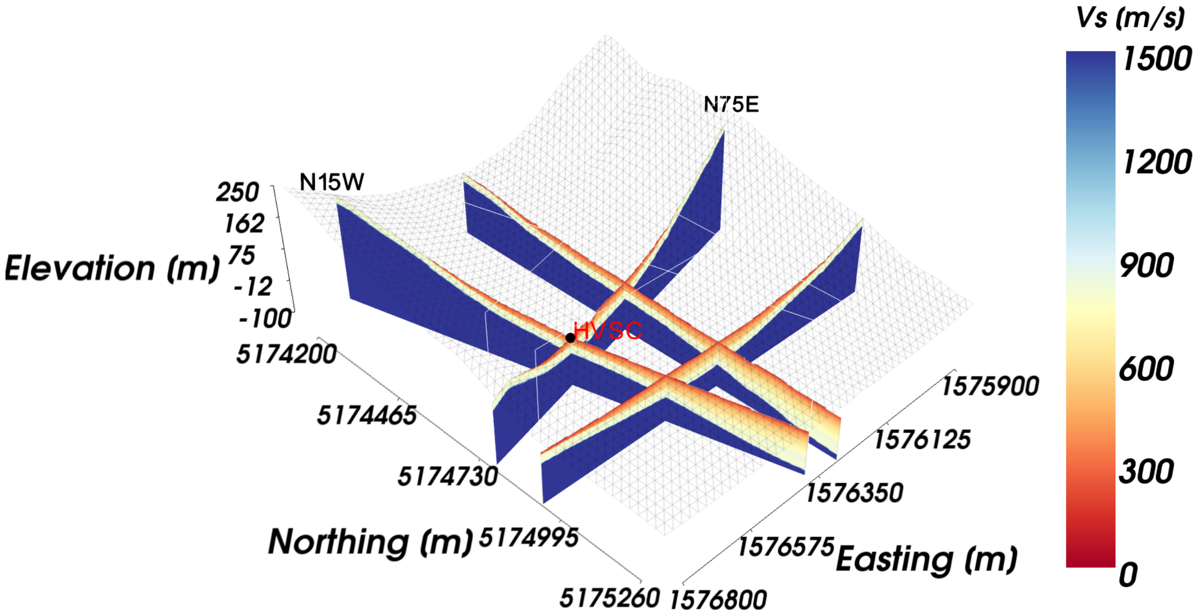


Figure 7: Fence diagrams showing the 3D V_S model of Heathcote Valley. Cross sections intersecting at HVSC are considered in 2D simulations. Northings and Eastings are in New Zealand Transverse Mercator 2000 (NZTM2000) projection.

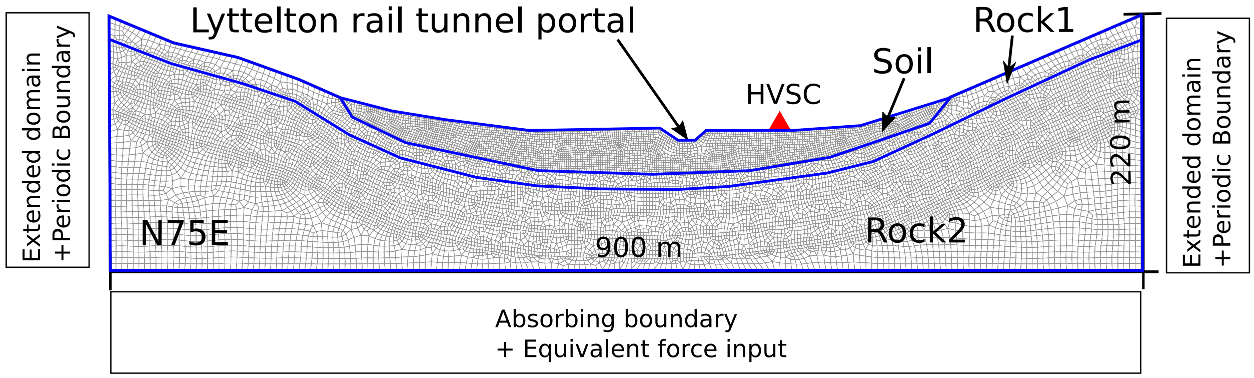


Figure 8: Two-dimensional mesh geometries and boundary conditions of the simulated valley cross section. See Table 1 for the material constitutive parametres.

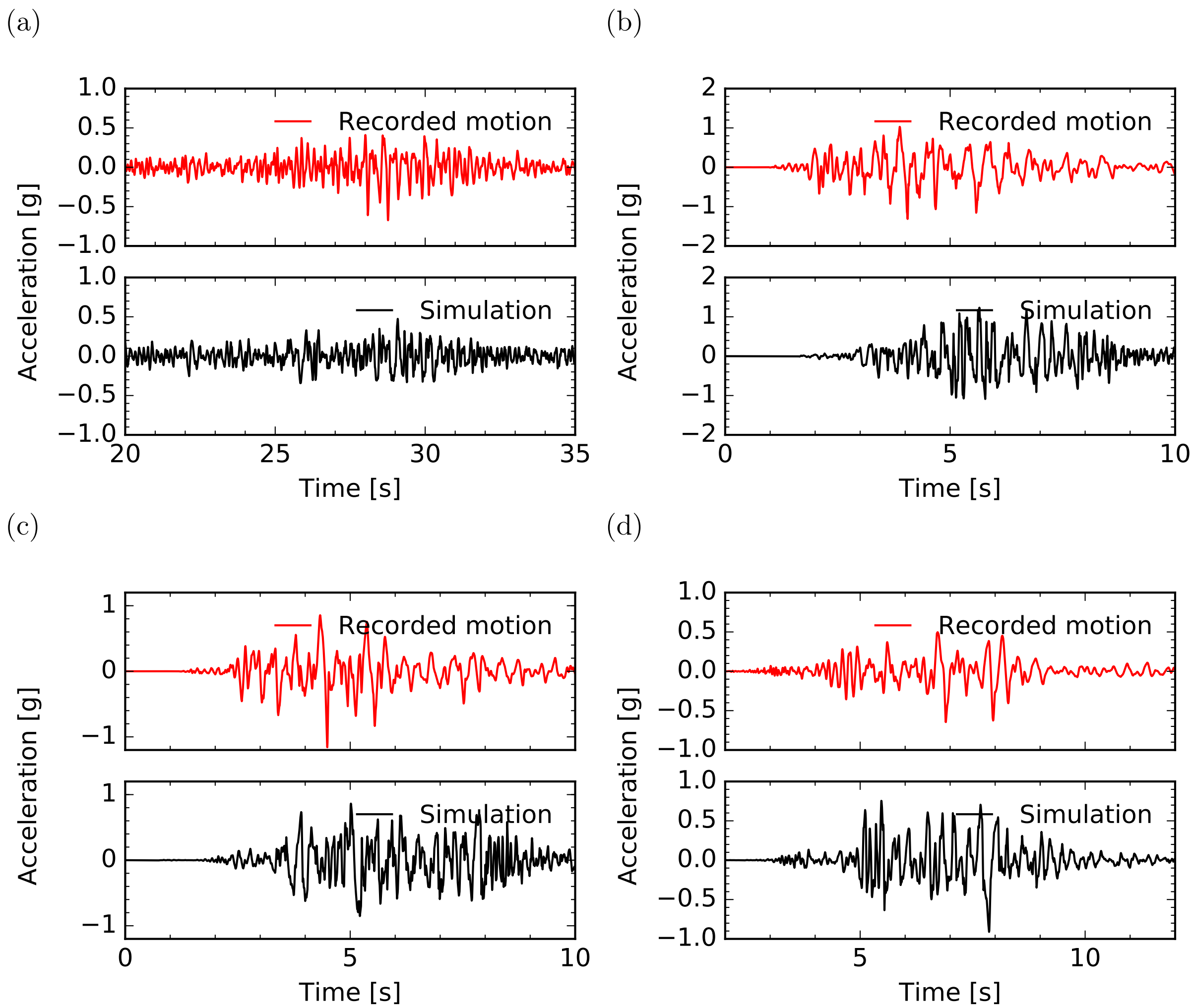


Figure 9: Comparison of acceleration time series for the four largest events: (a) 04/09/2010, (b) 22/02/2011, (c) 13/06/2011b, and (d) 23/12/2011b.

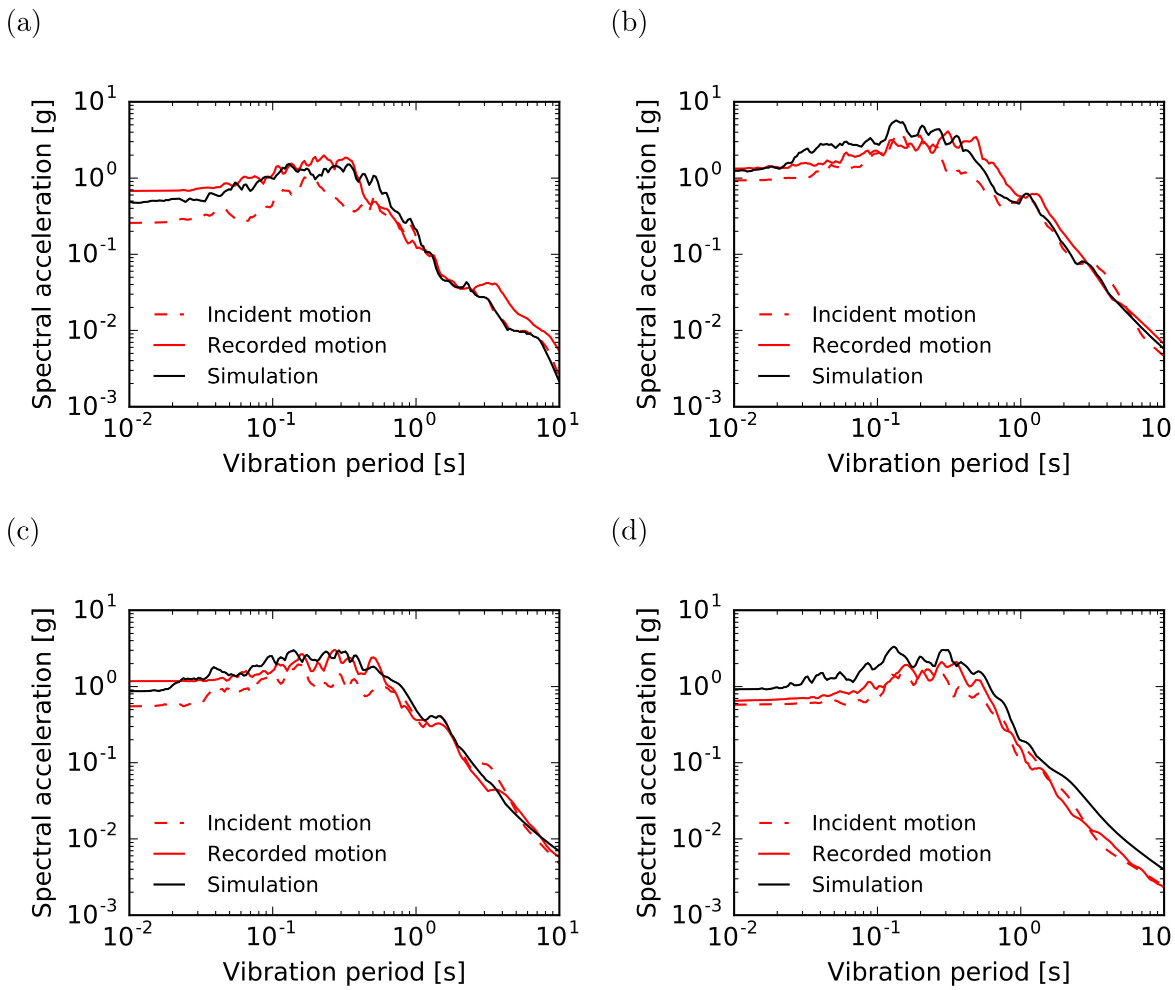


Figure 10: Comparison of acceleration response spectra for events: (a) 04/09/2010, (b) 22/02/2011, (c) 13/06/2011b, and (d) 23/12/2011b.

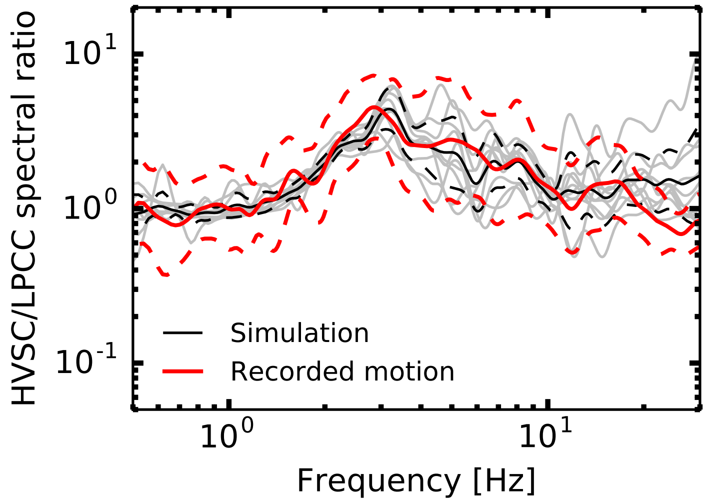


Figure 11: Comparison of simulated and recorded HVSC/LPCC Fourier spectral ratios for the 10 considered earthquake events. The thicker solid lines represent the median of the simulation and recorded motions and dashed lines represent the 16^{th} and 84^{th} percentiles.

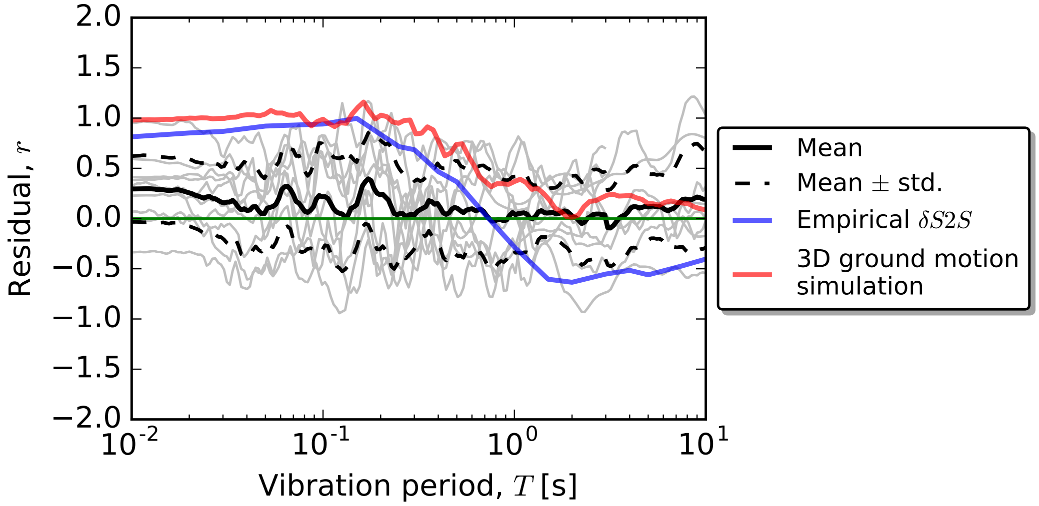


Figure 12: Mean and the confidence interval (16^{th} and 84^{th} percentile) of the residuals for all considered events based on 2D simulations. Mean residuals from the empirical prediction (Figure 5a) and from the broadband ground motion simulation (Figure 6) are shown for comparison.

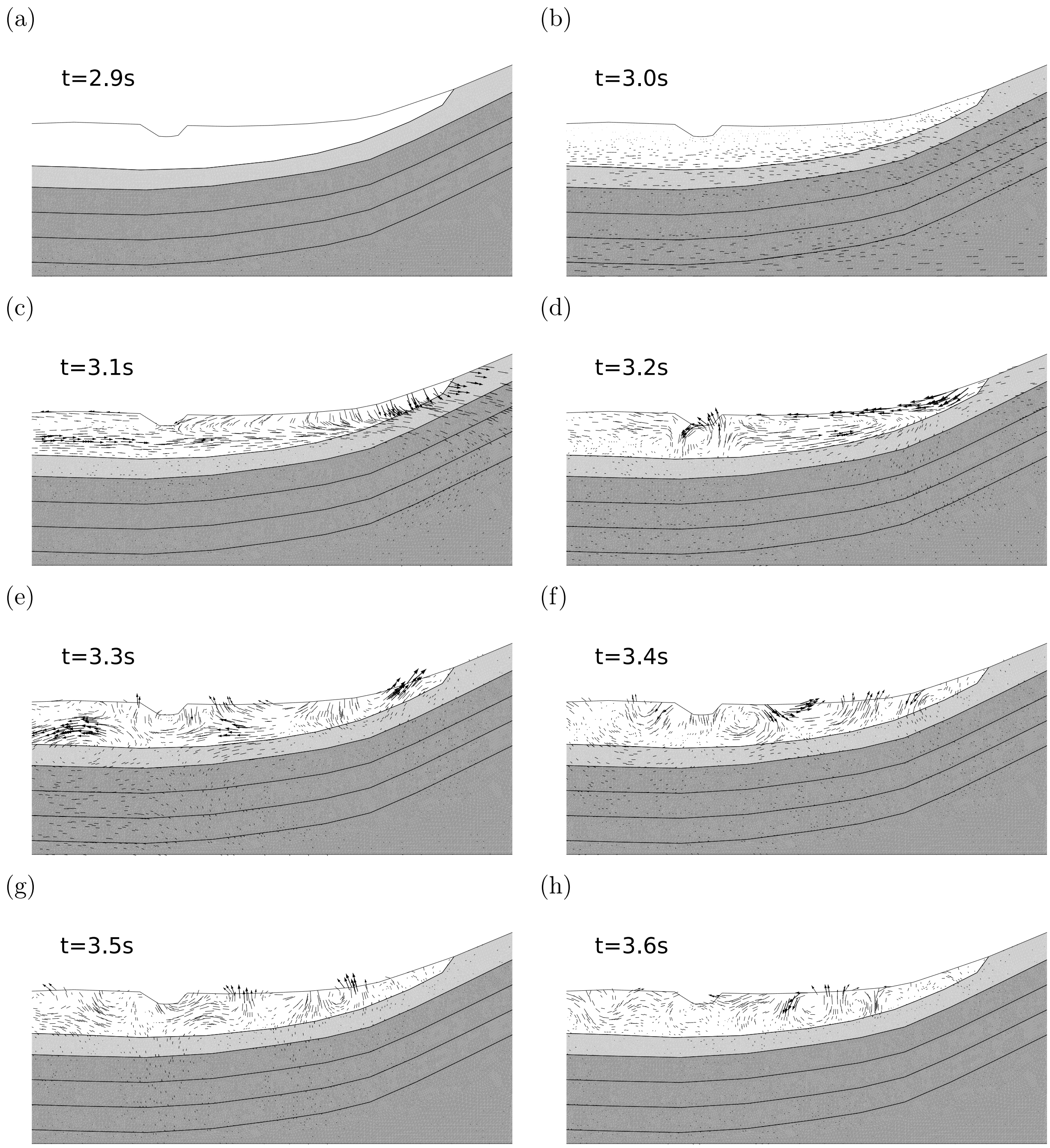


Figure 13: Snapshots of simulated particle velocity vectors for a Ricker wavelet with $f_0 = 6Hz$, and the arrival time of peak $t_0 = 3s$.

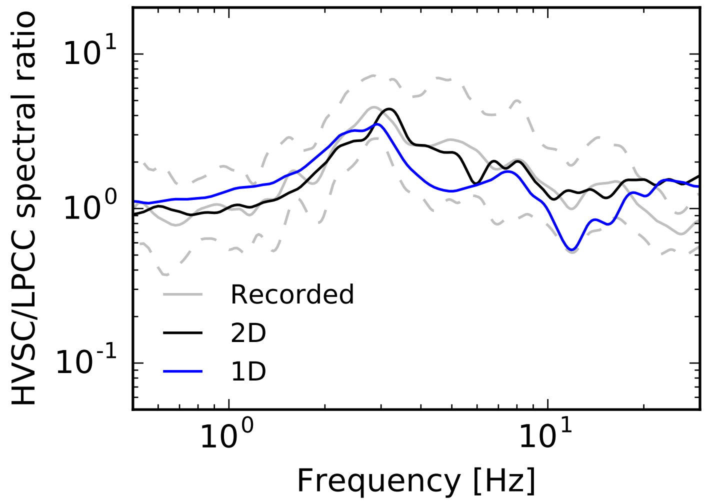


Figure 14: Effect of 2D site response on the median HVSC/LPCC Fourier spectral ratios. Dashed lines show the 16^{th} and 84^{th} percentiles for the recorded motions. For clarity, only the median spectral ratios are shown for the simulations.

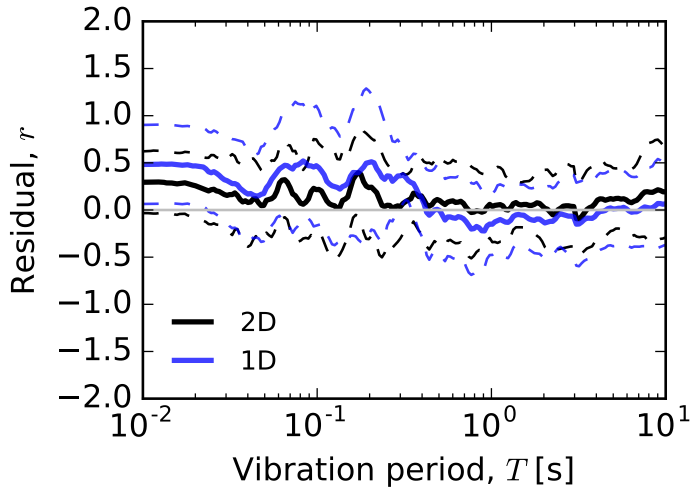


Figure 15: Comparison of mean SA residuals from 2D and 1D simulations. Dashed lines represent 16^{th} and 84^{th} percentiles.

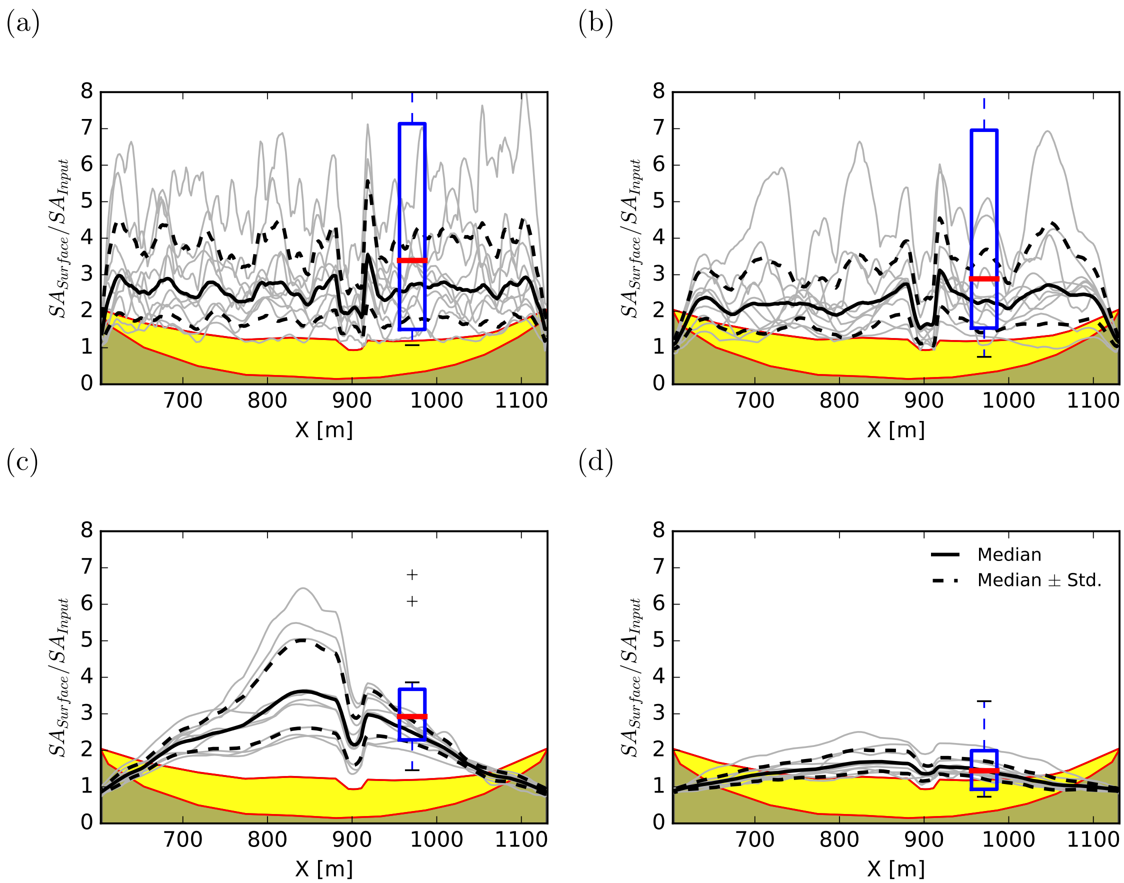
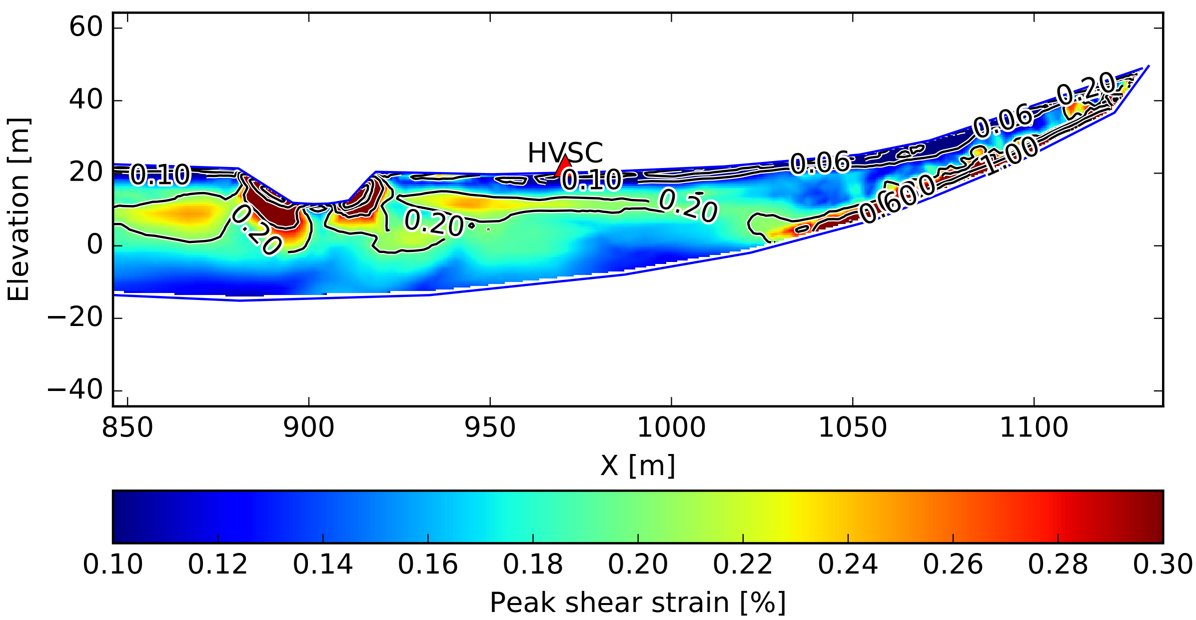


Figure 16: Simulated response spectral accelerations (horizontal component) for (a) $T = 0.1s$, (b) $T = 0.2s$, (c) $T = 0.4s$, and (d) $T = 0.8s$ along the surface of valley cross section. Recorded normalized spectral accelerations at HVSC are shown as box-and-whisker plots.

(a)



(b)

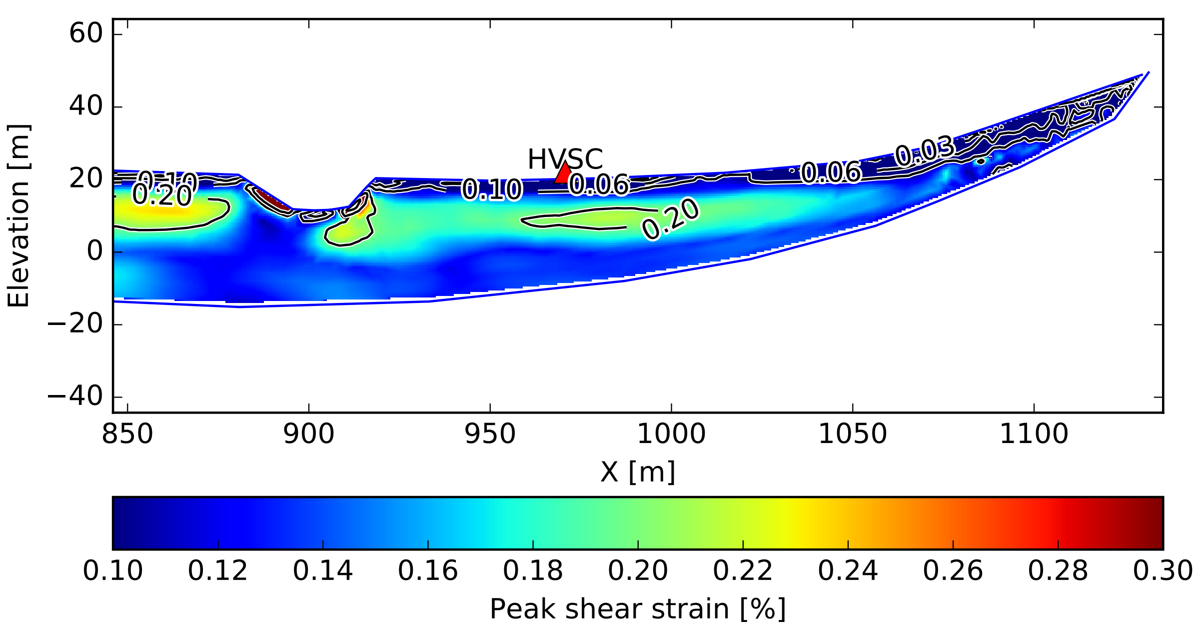


Figure 17: Simulated peak strain contour for earthquakes on: (a) 22/02/2011 and (b) 13/06/2011(b).

(a) (b)

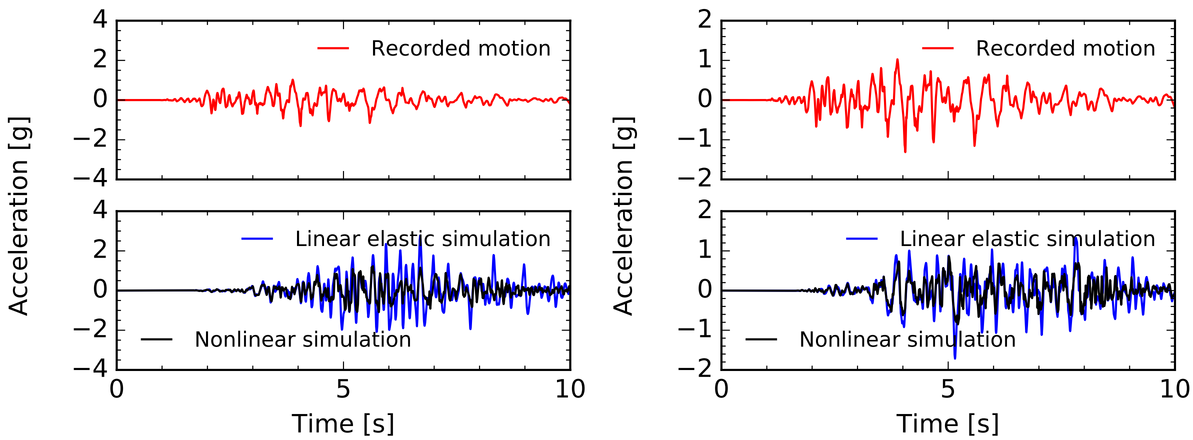


Figure 18: Recorded and simulated acceleration time series showing the effect of non-linear site response for earthquakes on: (a) 22/02/2011 and (b) 13/06/2011b.

(a) (b)

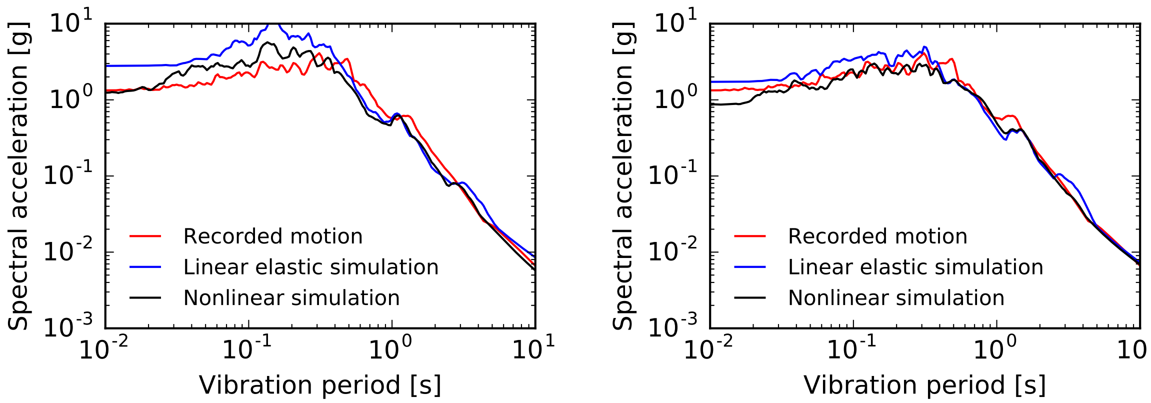


Figure 19: Simulated acceleration response spectra showing the effect of non-linear site response for earthquakes on: (a) 22/02/2011 and (b) 13/06/2011b.

(a) (b)

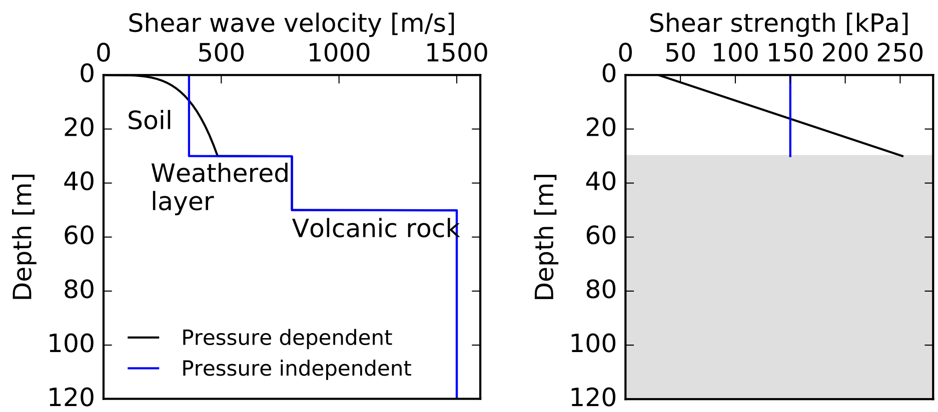


Figure 20: (a) Shear wave velocity profiles and (b) Shear strength profiles at HVSC based on pressure-dependent and pressure-independent soil models.

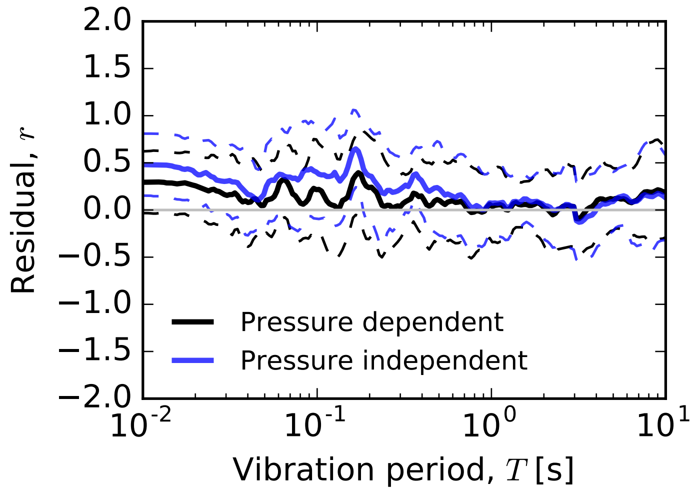


Figure 21: Effect of the pressure dependent shear modulus and strength of the soil on the simulated SA residual. Dashed lines represent 16^{th} and 84^{th} percentiles.

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